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Albert D. Rosellini, Governor

DEPARTMENT OF CONSERVATION
Earl Coe, Director

DIVISION OF WATER RESOURCES
Murray G. Walker, Supervisor

Water Supply Bulletin No. 20

GEOLOGY
and
GROUND-WATER RESOURCES
of
NORTHWESTERN KING COUNTY, WASHINGTON

By

Bruce A. Liesch, Charles E. Price and Kenneth L. Walters

Prepared in cooperation with
UNITED STATES GEOLOGICAL SURVEY
GROUND-WATER BRANCH

1963

Liesch, Bruce A.
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FOREWORD

A prerequisite to the orderly development and conservation of the State's ground-water resources is a thorough understanding of the geologic factors which control the storage and movement of ground water in and through the various rock materials which mantle the earth's surface. "Geology and Ground Water Resources of Northwest King County" was designed principally to furnish geologic and other basic data needed by those actually engaged in the development and distribution of both private and public water supplies serving the Seattle metropolitan area, one of the most rapidly expanding areas of the State of Washington and the United States.

It is recognized that the area's ground-water supplies alone are not adequate to satisfy the present and future water needs of northwest King County. However, with a planned orderly development they will serve the area's domestic, irrigation, and light industrial needs during its youth and will bridge the transition from a rural economy to urbanization. Ground water will also play an important role in and become a permanent part of the integrated water system needed to meet the ever-increasing needs of the metropolitan area.

In keeping with the policy of the Division of Water Resources and the U.S. Geological Survey, the material in Water Supply Bulletin No. 20 has been presented in a manner which makes it of value not only to those interested in water supply development but will also serve as a reference for geologists, engineers, and others working in associated fields which require a knowledge and understanding of the geologic factors which limit man's activity on and beneath the earth's surface.

"Geology and Ground Water Resources of Northwest King County" was prepared in cooperation with the U.S. Geological Survey, Ground Water Branch, as a part of the Division of Water Resources' overall inventory of the water resources of the State of Washington.

-Robert H. Russell
Assistant Supervisor
Division of Water Resources

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GEOLOGY AND GROUND WATER RESOURCES OF NORTHWESTERN KING COUNTY, WASHINGTON

By

Bruce A. Liesch, Charles E. Price, and Kenneth L. Walters

ABSTRACT

King County, in the west-central part of the State of Washington, includes about 2,135 square miles. The eastern part of the county lies in the Sierra-Cascade Mountains province and the remainder is in the Puget Trough of the Pacific Border province. The area covered by the present investigation is almost entirely within the Puget Trough and includes about 450 square miles.

The land surface consists principally of glacial drift plains which rise to altitudes of 600 feet above sea level and are separated by lakes or stream valleys. East-trending hills of sedimentary and volcanic rocks of Tertiary age occur along the southern boundary of the area and attain an altitude of over 2,200 feet.

The deposits exposed in the project area range in age from Eocene to Recent. More than half the surface of the area is mantled by glacial drift of Vashon age. The Vashon stratified drifts are the principal aquifers of the area; the older consolidated and unconsolidated deposits are of secondary importance.

The annual precipitation at Seattle ranges from about 19½ inches to about 56½ inches; the average is about 33½ inches. Most of the precipitation occurs during the late fall and winter; the summer is relatively dry.

Ground water in northwest King County is replenished almost entirely by precipitation on or near the area. Water levels in wells generally are within 100 feet of the land surface. Yields of wells in the area range from less than 10 gpm (gallons per minute) to as much as 500 gpm. Present ground-water use is principally for domestic and public supply.

The ground water of northwest King County is generally of good chemical quality. Only five wells are known to have yielded water containing more than 250 ppm (parts per million) of chloride. The high chloride content of the water from three of these wells was probably caused by salt-water intrusion and that of two may have been caused by incompletely flushed connate water (water trapped in the pores of sedimentary materials at the time of deposition). Several wells yield water that

contains more than 0.2 ppm iron. One well which taps Oligocene and Miocene marine sediments yields water containing 0.70 ppm of manganese. No other ground water in the area is known to contain more than 0.1 ppm manganese. Ground-water temperatures range from 45° to 50° F.

INTRODUCTION

Purpose and Scope of the Investigation

The investigation was made by the U.S. Geological Survey in cooperation with the Washington State Department of Conservation, Division of Water Resources, as part of a continuing program for the collection and interpretation of basic data concerned with ground-water supplies of the State of Washington.

The investigation was made because the project area is one of very rapidly increasing population; much of the water supplying the suburban area not served by the city of Seattle is obtained from ground-water sources. The rapid increase in population and the increased per capita consumption of ground water have resulted in many requests for data relating to ground water, indicating that a systematic appraisal of the ground-water resources of the area was needed.

The objective of the investigation was to gather, interpret, and present available data pertaining to the occurrence of ground water in northwestern King County and to make an appraisal of the quantity and quality of these supplies. The study also had as an objective the differentiation of the lithologic units and correlation of surface outcrops with subsurface features. The data collected during the study include records of wells and springs and information on the depth, thickness, and areal extent of the aquifers and their ability to store and transmit water, and on the sources of recharge and the direction of ground-water movement.

The investigation was made under the general direction of A. Nelson Sayre and Philip E. LaMoreaux, successive Chiefs, Ground Water Branch, U.S. Geological Survey, and Murray G. Walker, Supervisor, State Division of Water Resources, and under the direct supervision of A. A. Garrett, District Engineer, U.S. Geological Survey, and Robert H. Russell, Assistant Supervisor, Division of Water Resources.

The inventory of wells was made largely by D. E. Wegner, L. J. Gadbois, and B. A. Liesch during 1951-53 and was completed by K. L. Walters, G. D. Holmberg, and K. A. Jones in 1958-59. S. C. Awasthi, of the Geological Survey of India, assisted in the preparation of the report during August, September, and October 1958.

Location of the Area

The area covered by this investigation contains about 450 square miles in the northwestern part of King County, Wash., and includes the city of Seattle and the adjacent suburban area. It lies almost entirely within the Puget Trough section of the Pacific Border province (Fenneman, 1931, p. 443-454). On the west it is bounded by Puget Sound, on the east by the foothills of the Cascade Mountains, and on the north by the southern boundary of Snohomish County. On the south the project area is bounded by lat 47°30'N. from Puget Sound east to long 122°07'30"W., from there to the foothills it is bounded by the south edge of T. 23 N. The location of the project area in relation to the remainder of the county and to the State is shown in figure 1.

Previous Investigations

None of the previous investigations of the geology of northwest King County discussed ground-water features in detail; their scope was restricted largely to the stratigraphy and geologic history of the area. The first detailed study of the unconsolidated deposits of the Puget Sound lowland was made by Bretz (1910, 1913); his interpretation of the late Pleistocene lake sequence is a contribution of singular importance. The first detailed study of the consolidated rocks in South Seattle and at Alki Point was made by Weaver (1937, p. 152-154); he postulated that the Oligocene marine sediments exposed there are correlative with the Oligocene marine sediments exposed at Restoration Point on the other side of Puget Sound, about 3 miles west of Alki Point.

The consolidated rocks of the Newcastle-Grand Ridge hills were studied by Weaver (1937, p. 155-156) and by Warren and others (1945). The unconsolidated deposits of Seattle were described by Stark and Mullineaux in 1950. A soil survey report of western King County was prepared by Poulson and others in 1952, and an engineering soils manual to be used with that report was written by McLerran and Krashevski in 1954.

Many other papers about particular geologic problems of northwest King County are referred to where pertinent in this report. Valuable information on the geology and ground-water hydrology of adjacent areas was obtained from papers by Newcomb (1952) and Sceva (1957).

History of the Investigation

An investigation of the ground-water resources in an area east of Lake Washington was made by A. M. Piper and T. E. Eakin in 1944. The area included parts of Tps. 23 to 29 N., between Rs. 3 and 6 E. The results of that investigation were not published, although information was supplied informally to King County Water District 59.

In February 1951, B. A. Liesch of the Geological Survey began a ground-water investigation in the part of the northwest King County area that is east of Lake Washington. The initial phase of this investigation, which consisted of a collection of hydrologic data and a study of the geology, was halted in November 1952. Liesch started a similar investigation in the area west of Lake Washington in June 1953. So that the data collected in the area east of Lake Washington could be made available before completion of the expanded study, the well and spring records of that area were compiled by Liesch, and were released in February 1955 as an open-file report titled "Records of Wells, Water Levels, and Quality of Ground Water in the Sammamish Lake Area, King County, Washington" (Liesch, 1955).

In 1956, the investigation in and north of the city of Seattle--the area of expanded study--was recessed. In 1958, the work was resumed by C. E. Price with the assistance of G. D. Holmberg and K. A. Jones. The previous work was reviewed, and additional wells were canvassed to update the well inventory.

The geology of the Seattle South and Duwamish Head quadrangles was mapped in 1955 and 1959 by H. H. Waldron of the U.S. Geological Survey. Geologic mapping in the Shilshole Bay, Kirkland, Seattle North, and Mercer Island quadrangles was field checked in 1960 by D. R. Crandell, also of the Geological Survey. The report was written in 1959 from notes prepared by Liesch and from additional field reconnaissance studies as cited above. K. L. Walters, in charge of the project from April 1959 to its completion in 1960, designed many of the illustrations, and completed the checking of geologic mapping.

Acknowledgments

The well records presented in this report were obtained from well owners, users, and drillers. The friendly cooperation of these people is appreciated and acknowledged. Special thanks are given to H. O. Meyer, well driller of Kirkland, who gave free access to his files of well logs, and to Robinson and Roberts, consulting ground-water geologists of Tacoma, who supplied hydrologic data from their files. The helpful comments of Waldron and Crandell, who read the manuscript, are appreciated.

The data furnished from the files of the State of Washington Department of Conservation, Division of Water Resources; the Washington Toll Bridge Authority; the Washington State Highway Department; and the City of Seattle Engineering Department are gratefully acknowledged.

Well-Location Symbols

In this report wells are designated by symbols that indicate their location according to the rectangular grid system for subdivision of public land. For example, in the symbol 25/5-21M2 the part preceding the hyphen indicates successively the township and range north and east of the Willamette base line and meridian (T. 25 N., R. 5 E.). Because all townships in northwest King County are north and east of this base line and meridian, the letters "N" and "E" are omitted.

The first number after the hyphen indicates the section in which the well is located; the letter denotes the 40-acre subdivision of the section, according to the following diagram. The last number is the serial number of the well in the 40-acre subdivision. For example, well 25/5-21M2 is in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 21, T. 25 N., R. 5 E., and is the second well in that tract to be listed.

Springs are numbered in the same manner and the letter "s" is added. Thus, the first spring recorded in that 40-acre tract would have the number 25/5-21M1s.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

GEOGRAPHY

Topography and Drainage

Except for an area of about 30 square miles east of the Snoqualmie River, within the foothills of the Cascade Mountains, northwest King County is in the Puget Sound lowland, a topographic basin that extends from the Cascade Mountains on the east to the Olympic Mountains on the west. Most of northwest King County consists of extensive, gently rolling plains, commonly ranging in altitude from 200 to 600 feet. The drift mantling these plains was deposited by the latest (Vashon) glacier, and the numerous surface depressions left by the retreating glacier are now occupied by small lakes and peat bogs. The plains are separated by broad-floored north-trending major valleys, which are underlain by deposits of Recent age. The steeply sloping valley walls have been included with the drift plains; only the valley floors are included in the discussions of the valleys. In the southern part of northwest King County, an east-trending ridge of bedrock hills--the Newcastle-Grand Ridge hills (fig. 1)--rises more than a thousand feet above the drift plains. These hills are composed of Tertiary rocks thinly mantled by Vashon drift.

In northwest King County, the surface of the Vashon glacial drift has not been greatly modified by postglacial erosion; however, spring-fed streams have cut short, steep-sided canyons into the margins of the drift plains, and many slopes adjacent to Puget Sound have been steepened by wave erosion.

Listed generally from west to east, arbitrary but convenient designations for the physiographic units of the area are as follows:

West Seattle drift plain
Duwamish River valley floor
Seattle drift plain
Mercer Island
Interlake drift plain
Newcastle-Grand Ridge hills
Sammamish River valley floor
Eastern drift plain
Snoqualmie River valley floor
Cascade foothills

These units are shown on figure 1, though their boundaries are not everywhere definite.

Most of northwest King County is drained either by the Snoqualmie River or by the Lake Washington canal; some of the area west of Lake Washington is drained by the Duwamish River and by short streams flowing directly into the Sound.

Climate

The Puget Sound lowland has an equable climate. Because of its nearness to the Pacific Ocean and because the prevailing winds blow from the ocean, extremes in temperature are uncommon. Moderate to heavy precipitation occurs in the winter. Although some rain may fall during the summer, this season is generally dry. To the east, in the Cascade Mountains and foothills, precipitation is heavier than in the lowland, and much of the precipitation is snow. In northwest King County, as elsewhere in the Puget Sound lowland, local variations in precipitation, temperature, and wind direction and intensity are caused by the irregular relief of the area.

Precipitation

Precipitation, averaging about 30 to 35 inches a year in northwest King County,usually occurs in the form of a drizzle or light rain. Thunderstorms are uncommon and average only about five a year. Approximately 70 percent of the precipitation occurs in the 6-month period October through March, some precipitation occurring almost every day during the winter. December is the wettest month and July or August is the driest (fig. 2).

The isohyetal map of King County (fig. 3) shows that the area of greatest recorded precipitation is not at the crest of the Cascade Mountains as might be expected, but rather on the western flank, some 10 or 15 miles west of the divide. For example, the greatest average annual precipitation recorded in the county is at Cedar Lake, about 13 miles west of the crest of the Cascade Mountains. At the crest, specifically at Snoqualmie Pass, the average precipitation is about 92 percent of that at Cedar Lake. The greatest precipitation at Seattle during the period 1878-1956 was 56½ inches, in 1879, and the least was 19½ inches, in 1952.

Temperature

The average annual temperature at Seattle for the 67-year period, 1890-1956, is 53.2°F; July is the warmest month, with an average temperature of 65.6°F, and January is the coolest, with an average temperature of 40.7°F. The frost-free period is about 260 days on the average. These temperature data probably are fairly typical of the entire northwest King County area. At the Seattle weather station, the highest temperature for the period of record was 100°F, on July 16, 1941, and June 9, 1955; the lowest was 3°F, on January 31, 1893.

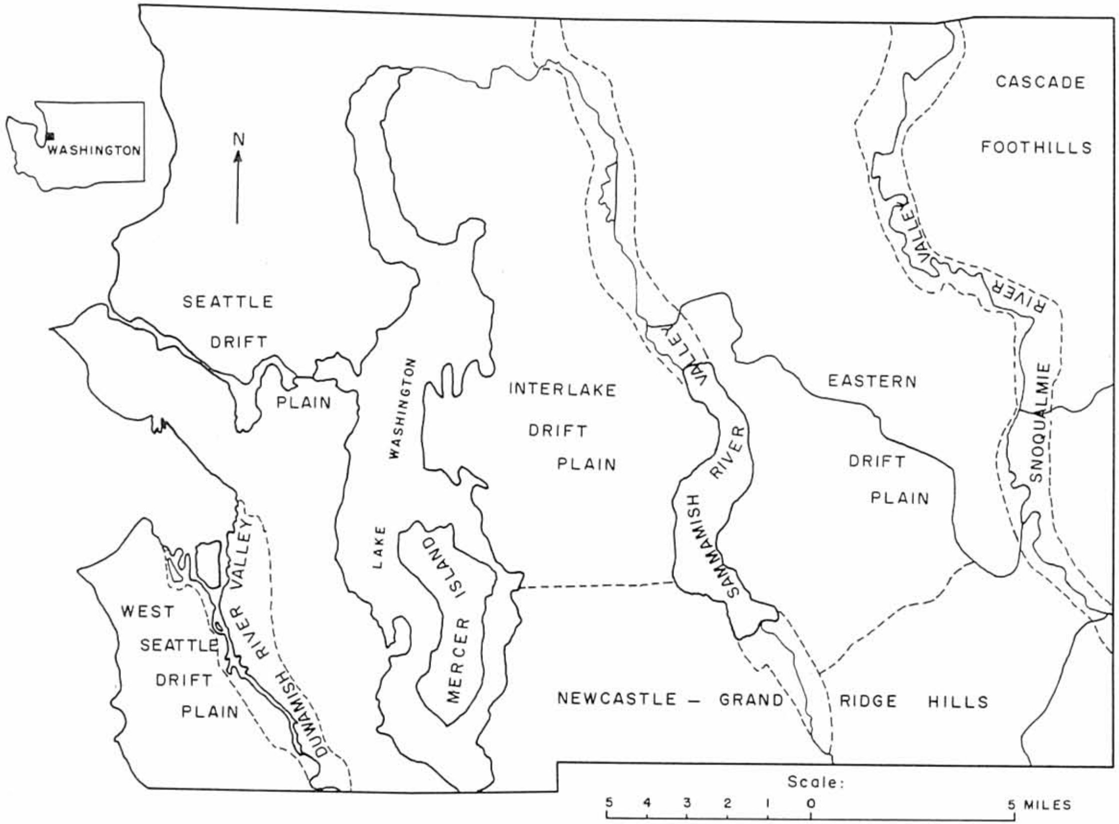


Figure 1.-- Map of northwestern King County showing principal topographic units.

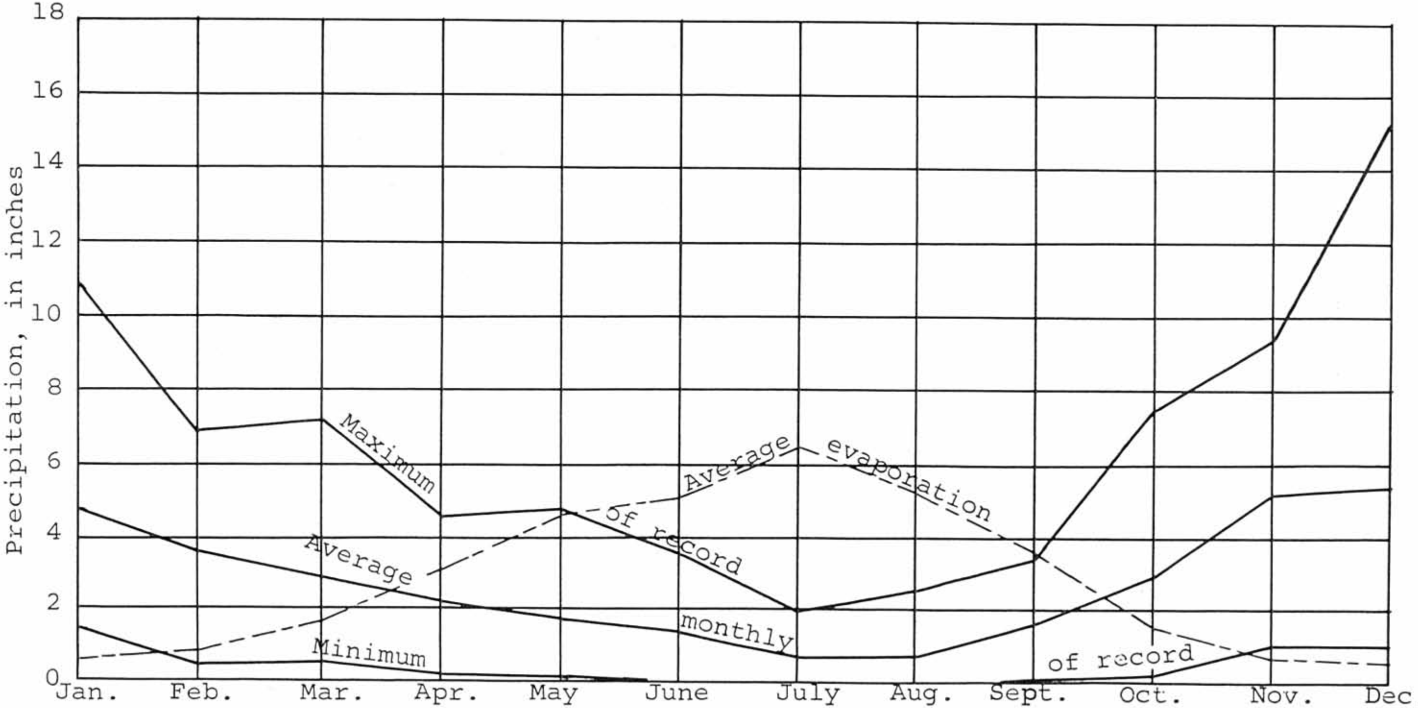
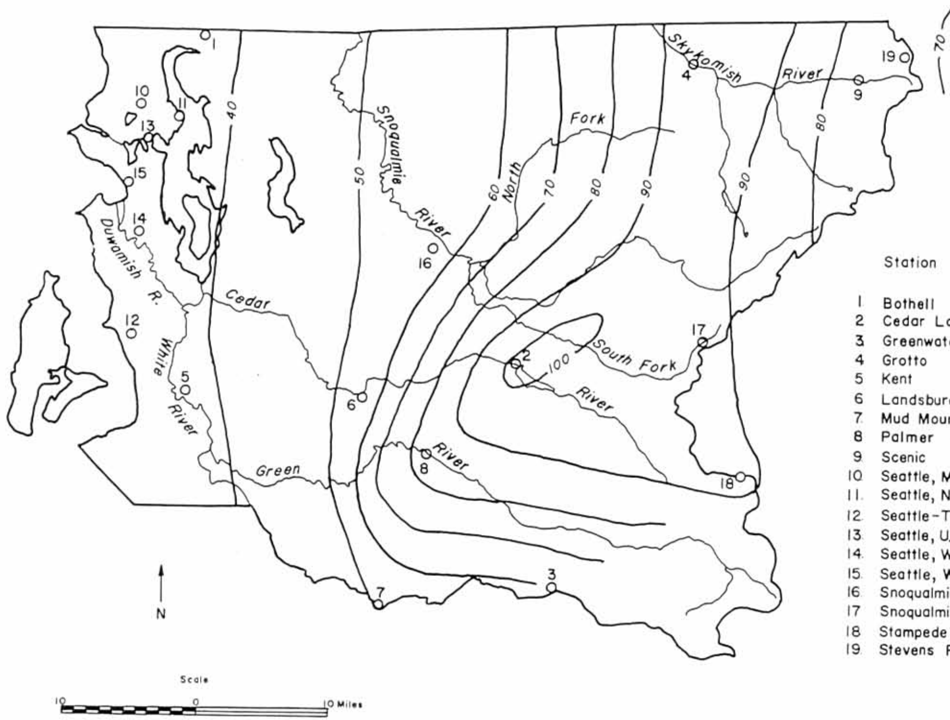


Figure 2.--Monthly precipitation at Seattle for the period of record, 1905-56 and average evaporation for the period 1941-53.



	Station	Altitude Feet	Average Annual Precipitation (Inches)
1	Bothell	105	38.10
2	Cedar Lake	1560	103.30
3	Greenwater	1708	59.00 est.
4	Grotto	849	96.00 est.
5	Kent	40	36.59
6	Landsburg	535	53.01
7	Mud Mountain Dam	1308	50.09
8	Palmer 3 SE	895	86.04
9	Scenic	2224	75.35
10	Seattle, Maple Leaf Res.	422	30.68
11	Seattle, Naval Air Station	21	30.87
12	Seattle-Tacoma, Weather Bur. Airport	386	33.93
13	Seattle, U. of Wash.	60	32.04
14	Seattle, Weather Bur. Airport	14	34.28
15	Seattle, Weather Bur. City	14	31.92
16	Snoqualmie Falls	440	55.19
17	Snoqualmie Pass	3020	94.74
18	Stampede Pass	3963	93.99
19	Stevens Pass	4085	72.52

Data from U.S. Weather Bureau

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Isohyetal lines based on precipitation records for the period from the establisment of each station through 1956. Interval 10 inches.

Figure 3 – Map of King County showing location of weather stations and the average annual precipitation.

Evaporation

The rate of evaporation from much of the project area doubtless is comparable to that at Seattle, where the evaporation at Maple Leaf Reservoir during the period from 1941 to 1953 was less than 1 inch in December and January and about 6 inches in July (fig. 2). Because the period of lowest evaporation coincides with the period of highest rainfall, much of the precipitation may be expected either to enter the ground and recharge the ground-water body or to leave the area as surface runoff.

Culture and Industry

Seattle, having a population estimated at about 557,000 in 1960, is the largest city in the State and dominates the northwest King County area.

The principal industries of Seattle include the manufacture of airplanes, food processing, fabrication of metal products, and lumber. Coal mining was formerly a very important industry in the Newcastle Hills, but is now mined only on a small scale. Sand and gravel are produced from several large pits in northwest King County, notably at Issaquah, in the Kenmore area, at Kirkland, in the Redmond area, and in South Seattle.

Farming is carried on in the Duwamish, Snoqualmie, and Sammamish River valleys. The soils in these valleys are predominantly silty clay to very fine sandy loam, and are particularly suitable for truck and dairy farming. In general, the stony soils of the drift plains are not as suitable for agriculture as are the soils in the major valleys.

Vegetation

Many years ago the native vegetation of northwest King County was dominated by conifers. Virtually all the native evergreen timber has been cut, and the areas logged have been taken over, in many places, by bigleaf maple, vine maple, red alder, and willow. In many of the low moist areas, alder and willow predominate.

Of the common plants of northwest King County, only the willow is known to obtain its water supply from the zone of saturation. Such a plant is known as a phreatophyte. However, black cottonwood is commonly associated with the willow and is probably also a phreatophyte. Locally at least, alder may be a phreatophyte. According to Robinson (1958, p. 62-64), willow grows principally where the depth to water is less than 15 feet, and cottonwoods probably do not grow where the depth is much more than 30 feet. The consumptive use of water by willows and cottonwoods in the project area is not known, but may be large locally. Owners of shallow wells and springs may find that, at least locally, yields can be increased substantially by removal of water-consuming vegetation adjacent to the wells or springs.

GEOLOGY

General Features

The rocks of northwest King County have been divided into two principal groups: (1) consolidated bedrock of Tertiary age, and (2) semiconsolidated to unconsolidated deposits of Pleistocene and Recent ages. In the eastern and south-central parts of the area (pl. 1) Tertiary rocks crop out at altitudes of several hundred feet above sea level; in the northwestern part of the area the Tertiary rocks are buried beneath several hundred feet of unconsolidated deposits. In the south-western part of the area, in Seattle, Tertiary rocks are exposed at altitudes ranging from a few to about 300 feet above sea level. Stratigraphic relations and structure are shown by the cross section on plate 2.

The Tertiary rocks were not studied in detail during this investigation because the work of Warren and others (1945) and of H. H. Waldron (written communication, 1959) were sufficient for the present study. The terminology and description of the Tertiary rocks are largely after Warren and others (1945), but the contacts between the bedrock and surficial units have been modified. The geology of the Tertiary rocks of the South Seattle and Duwamish Head quadrangles is after Waldron (written communication, 1959). Unconsolidated deposits, all of which are probably of Quaternary age, mantle much of northwest King County. These deposits occur at altitudes ranging from more than 1,000 feet above sea level to several hundred feet below sea level (pl. 2, sec. C-C').

Consolidated Rocks

The consolidated rocks of northwest King County range in age from Eocene to Miocene. These rocks consist chiefly of shale, graywacke, sandstone, conglomerate, and andesite. They are exposed only in the southern part of the project area. Only small supplies of ground water currently are developed from the consolidated rocks.

Eocene Continental and Marine Sedimentary Rocks

According to Warren and others (1945), the oldest rocks exposed in the mapped area are part of a sequence of over 2,000 feet of "continental and marine carbonaceous shale, fossiliferous graywacke, and conglomerate" of Eocene age. These rocks crop out in several places within a mile or so of Preston in the valleys of the East Fork of Issaquah Creek, the Raging River, and an unnamed creek west of Preston. The unit is exposed also in the Duwamish River valley near West Duwamish. Age determination of fossils from an exposure half a mile west of Preston suggests that these beds are of late Eocene age (Warren and others,1945). They may, however, be as old as middle Eocene on the basis of the age of fossils from exposures in the Duwamish River valley (Waldron, oral communication, 1959).

Eocene Volcanic Rocks

Several thousand feet of tuffaceous andesitic sandstone and volcanic breccia separate the Eocene continental and marine sedimentary rocks from the arkosic rocks of the Puget group. These volcanic rocks are extensively exposed in the Newcastle-Grand Ridge hills. Warren and others (1945) suggest that because their maximum thickness of 7,000 feet is in the vicinity of sec. 1, T. 23 N., R. 6 E., their source may be in that locality.

Puget Group

Interbedded sandstone, shale, and coal of the Puget group of probable late Eocene age (Warren and others, 1945) crop out in the southern part of the area. Bedding in the sandstone varies from thick to thin; thicker beds are commonly cross-bedded. Where mapped by Warren the Puget group is 3,000 to 3,200 feet thick.

Keechelus Andesitic Series

According to Warren and others (1945), the Puget group is overlain by the Keechelus andesitic series in the eastern part of the King County coal field and by marine sedimentary beds in the western part of the field. On the basis of faunal evidence, the marine sedimentary beds, discussed in the next section, are considered to be of middle Oligocene to early Miocene age. Because of the stratigraphic position of the Keechelus andesitic series with respect to the marine sedimentary beds, and because of the presence of tuff apparently derived from Keechelus volcanism in the marine sedimentary beds, Warren believed that the two are of the same age span.

Andesite flows west of Grand Ridge, in secs. 22 and 23, T. 24 N., R. 6 E., mapped as Keechelus by Warren and others (1945), lie at or near the base of the Oligocene and Miocene marine sedimentary beds. Locally, beyond the map area, a continental facies of the marine sedimentary beds is capped by a flow of the Keechelus.

The Keechelus andesitic series consists of tuffs and flows of basic andesite. In northwest King County the series is exposed in only a few small patches west of Grand Ridge. No tuffs were observed in this exposure. On plate 1 these volcanic rocks have been included with the older volcanic rocks (Eocene). Although Warren noted that east of R. 7 E. the Keechelus andesitic series probably is more than 10,000 feet thick, its thickness in the area of this investigation is not known.

Oligocene and Miocene Marine Sedimentary Rocks

Beds of marine sandstone, shale, and minor amounts of conglomerate of middle Oligocene and early Miocene age undifferentiated are exposed at scattered localities throughout northwestern King County (pl. 1). According to Warren and others (1945) this unit may be as much as 8,000 feet thick in sec. 13, T. 24 N., R. 5 E., along U.S. Highway 10 northwest of Issaquah. Here, the rocks of this sequence are composed of thin strata of conglomerate and thicker beds of fossiliferous, tuffaceous sandstone and sandy shale. Warren and others (1945) state that, according to C. E. Weaver, fossils at this locality belong to the fauna of the Sooke formation, which Weaver (1937) considered to be of earliest Miocene age. Warren also found fossils of middle Oligocene age near the base of the series here.

The exposure of these Oligocene and Miocene sedimentary rocks on the Seattle drift plain just west of Bailey Peninsula is the largest in the project area. The stratigraphy and fauna of these rocks have been studied in detail by Weaver (1937, p. 152-154) and by Durham (1944, p. 130) and are being studied currently by Waldron of the Branch of Engineering Geology, U.S. Geological Survey.

According to Waldron (written communication, 1958), the beds of Oligocene age exposed in South Seattle and at Alki Point consist of sandstone, siltstone, shale, and minor amounts of conglomerate. The lowest beds composed chiefly of sandstone and siltstone are exposed at South Park, in secs. 32 and 33, T. 24 N., R. 4 E., and on the west flank of the Seattle drift plain near Georgetown. Some of the beds are pumiceous and contain carbonized fragments of plants. Overlying this sandstone and siltstone unit is a band of conglomerate, which crops out discontinuously from Bailey Peninsula to Georgetown. The measured thickness of this conglomerate is about 400 feet, according to Weaver (1937, p. 153). It is well exposed on the west side of Bailey Peninsula (Seward Park) and along 15th Avenue South near the S.E. cor., sec. 20, T. 24 N., R. 4 E. In general, the rock is massive, poorly sorted and moderately well compacted. The fragments are chiefly pebbles, though they range in size from very coarse sand to boulders. The pebbles are composed of a variety of rock types including andesite, basalt, quartzite, rhyolite, and chert; only rarely are granitic pebbles found.

Above the conglomerate lies a series of interbedded shale, siltstone, and very fine sandstone. Typical exposures of these beds occur along the east side of Duwamish River valley, in the SE¼SE¼ sec. 20, T. 24 N., R. 4 E. They are light gray to brown, highly fractured, and rather poorly bedded. The thickness of these beds is more than 1,000 feet (Waldron, written communication, 1959).

The beds that crop out at Alki Point (in secs. 10 and 15, T. 24 N., R. 3 E.) consist of 465 feet of siltstone (Weaver, 1937, p. 152-153) and minor amounts of very fine to coarse sandstone and some shale and mudstone. Most of the rocks are micaceous and some are tuffaceous; many contain fossils. On the basis of faunal and lithologic similarities, the beds of Oligocene age exposed at Alki Point and in South Seattle have been correlated with the type Blakeley formation of Weaver (1916, 1937) in Kitsap County to the west (Durham, 1944, p. 130).

Structure

The Tertiary rocks of the area have been folded and faulted. Some movement may have taken place while the Puget group was being deposited, but most of it occurred in Miocene time after the eruption of the Keechelus andesitic series had ceased and the Oligocene and Miocene sedimentary beds had been deposited (Warren and others, 1945).

The most pronounced fold in the area is the Newcastle Hills anticline described by Weaver (1937, p. 155). The axis of this anticline extends from near the south end of Lake Boren, in the NW¼NW¼ sec. 34, T. 24 N., R. 5 E., through sec. 35, to about 2 miles south of High Point, then southeast across T. 23 N., R. 7 E. The north limb of the Newcastle Hills anticline dips as steeply as 47°; the south limb, which also dips steeply, is overturned in sec. 2, T. 23 N., R. 5 E. (Warren and others, 1945). According to Weaver (1937, p. 198), the anticline extends to the west through South Seattle and across Puget Sound into central Kitsap County. In South Seattle several minor cross folds occur on both flanks of this major anticline. Those on the north flank plunge generally to the north and those on the south flank plunge generally to the south. At Alki Point the Oligocene sedimentary beds form the nose of a small steeply dipping anticline that plunges to the north.

Unconsolidated Rocks

The unconsolidated rocks in northwest King County consist chiefly of gravel, sand, silt, and clay, of Quaternary age. The maximum known thickness of the unconsolidated rocks here is 1,235 feet, at well 24/4-18B1. Water-bearing zones in the sequence of unconsolidated rocks yield virtually all the ground water developed for economic use in northwest King County.

Stratigraphic names were first applied to the unconsolidated deposits of the Puget Sound area by Willis (1898). He and Smith (Willis and Smith, 1899) mapped these deposits in the Tacoma 30-minute quadrangle, immediately south of the northwest King County area.

The unconsolidated deposits of northwest King County were mapped principally by Bruce Liesch in 1951-53, who made tentative correlations of these deposits with those mapped in the Tacoma quadrangle by Willis and Smith (1899). At the time this report was in preparation, criteria had not been found for establishing firm correlation between the formations and those of Willis and Smith in northwest King County. For that reason, except for deposits of the Vashon glaciation, informal names are used here. This procedure also was used by Newcomb (1952) when he investigated the unconsolidated deposits in the western part of Snohomish County in 1946. Because of the relatively great distance to the area mapped by Willis and Smith, Newcomb decided to set up local stratigraphic names rather than to attempt correlation.

For the northwest King County area, the sequence of unconsolidated units was determined from isolated exposures of the contacts, from well logs (table 7), and from a study of the surface features peculiar to certain types of deposits.

During the investigation an attempt was made to locate an exposure in which the relationship of several of the pre-Vashon unconsolidated deposits could be established. The best exposure found during the course of the investigation is the cut on the northwest side of Siler Road in the NW¼NE¼ and NE¼NW¼ sec. 17, T. 25 N., R. 6 E. However, the contacts between some of the units are disturbed by what is probably a slump feature; some beds are vertical, and their relationships are not clear.

The base of the unconsolidated deposits is impossible to recognize from many drillers' logs because the descriptions of the drill cuttings are very generalized. Drilling speed, which might give an indication of the type of material being drilled, generally was not recorded, so that in many wells, where the unconsolidated materials may have been completely penetrated, their exact thickness cannot be determined from the logs.

Older Unconsolidated Deposits

In northwest King County a sequence of interbedded sand, silt, and clay, containing minor amounts of gravel, till, and volcanic ash, overlies the Oligocene and Miocene marine sedimentary rocks. These unconsolidated deposits are called the older unconsolidated deposits in this report.

From interpretation of well logs it appears that the upper surface of the older unconsolidated deposits lies approximately at sea level beneath the east shore of Lake Washington. Eastward from Lake Washington the top of these deposits slopes upward to an altitude of more than 100 feet above sea level in R. 7 E. The older unconsolidated deposits were eroded prior to deposition of overlying deposits, and the surface is cut by valleys which subsequently have been partly or completely filled; Lake Sammamish probably occupies such a valley. West from Lake Washington, the surface of the older unconsolidated deposits slopes much more steeply downward, and in T. 25 N., R. 3 E., the top of these deposits appears to be several hundred feet below sea level. The maximum inferred thickness of these deposits is over 1,000 feet, at well 24/4-18B1. The only known outcrop is in the SW$\frac{1}{4}$ sec. 12, T. 24 N., R. 5 E., where about 100 feet is exposed. There the older unconsolidated deposits are moderately compacted and consist of beds of silt, sand, tuff, and lapilli. The silt and sand is pale to dark yellowish gray, brown, or red and is massive to laminated. Commonly it has well-developed joints which are spaced less than 1 foot apart and have a dark-yellowish-orange (hydrous iron oxide?) staining. The sand is well sorted, medium grained, and composed of subrounded to angular clastic fragments, about half of which are white to light-gray crystalline material (probably quartz and feldspar) and about half are dark colored. Some beds, composed predominantly of sand, contain granules and pebbles as large as half an inch in diameter, and some beds also contain slightly altered tuff and grains of hypersthene.

The beds of tuff and lapilli are varicolored; yellowish-gray, medium- to very light-gray, pale- to dark-yellowish-orange, and pale-red-purple hues predominate. The individual volcanic ejecta are subrounded to subangular. Field examination indicates that some of the beds contain as much as 15 percent biotite, 5 percent transparent white crystals which are probably quartz and feldspar, 5 percent dark hard-rock fragments and 1 percent plant fragments. Commonly the larger lapilli have a thin coating of a dark-yellowish-orange material that may be hydrous iron oxide.

According to D. R. Mullineaux of the U.S. Geological Survey (oral communication, 1959) the Miocene deposits in the southeastern part of the Puget Sound lowland east of Tacoma do not contain large quantities of hypersthene. Therefore, the sand beds cropping out in the SW$\frac{1}{4}$ sec. 12, T. 24 N., R. 5 E., probably are no older than Pliocene, and because they are more indurated than any other post-Miocene sand beds in the area, they are believed to be correlative with the older unconsolidated deposits.

Lower Clay Unit

A unit about 50 feet thick, composed almost entirely of gray, blue, and brown clay and silt, overlies the older unconsolidated deposits and immediately underlies a gravel bed in the northwest King County area. This clay and silt unit is referred to in this report as the lower clay. It is thick bedded to laminated and was deposited in large part in standing water. Locally the clay is varved.

Some discontinuous beds of till are present in the lower clay unit and commonly these also contain a large percentage of clay and silt. At several places in Seattle where the lower clay is exposed it contains beds of woody peat. The most extensive exposures are along the west shore of Lake Washington, in secs. 27 and 34, T. 26 N., R. 4 E. Several beds of peat, up to 1 foot in thickness are interbedded with clay, silt, and fine pumiceous sand. The presence of beds of both glacial till and woody peat in the lower clay probably indicates deposition during both glacial and nonglacial times.

Locally, it was impossible to determine the position of the contact between the lower clay and the older unconsolidated deposits on the basis of drillers' logs. For that reason, these two are shown as undifferentiated in some parts of section B-B' on plate 2.

The lower clay unit may be correlative in part with the unit termed the Admiralty till and clay by Willis (1898). However, no reliable criteria are known upon which a correlation may be based. The units mapped as the Admiralty clay by Newcomb (1952) and Admiralty drift by Sceva (1957) probably are correlative with the older unconsolidated deposits and the lower clay unit of this report.

Unnamed Gravel

A sequence of cobble, pebble and granule gravel and sand, called the unnamed gravel in this report, disconformably overlies the lower clay unit. Where exposed, the gravel is weathered to a yellowish brown; pebbles of volcanic rocks commonly have alteration rinds and many pebbles of granitic rock have completely disintegrated. Where encountered in drilling, however, the gravel is typically gray and appears fresh and unaltered.

The unnamed gravel crops out along the sides of the uplands, and ranges in thickness from 0 to more than 200 feet; for example, it is exposed along the west shore of the north end of Lake Washington about 50 to 75 feet above lake level almost continuously for about 2 miles south of Sheridan Beach. Locally along Puget Sound the base of the unnamed gravel is below sea level. The gravel grades laterally from cobble, pebble, and granule gravel and sand in the eastern part of the project area to predominantly granule gravel and sand in the western part. In the vicinity of Seattle the unit grades vertically from granule gravel at the base to sand at the top.

The unnamed gravel probably is correlative with the lower member of the Orting gravel mapped by Sceva (1957) in Kitsap County. It may also be correlative with gravel and sand in the Admiralty clay of Newcomb (1952, p. 45) in Snohomish County.

Upper Clay Unit

Beds of finely laminated to massive gray, brown, and blue-gray silt and clay, locally more than 200 feet thick (pl. 2, sec. A-A'), overlie the unnamed gravel; these are referred to as the upper clay unit. Evidence showing that at least part of the upper clay was deposited during a nonglacial time is present in several exposures. One such exposure is in a cliff along the west shore of Lake Washington about 3 miles north of Sand Point, in the SE¼SW¼ sec. 15, T. 26 N., R. 4 E. There a bed of silty peat 2 inches thick is exposed in the upper clay unit about 50 feet above its contact with the unnamed gravel. Willow leaves and small fragments of wood identified as Salix, sp., by R. W. Brown, U.S. Geological Survey occur about 20 feet above the peat bed. In a sea cliff about 4 miles directly west of the outcrop just described, two beds of purple silty peat are interbedded with silt and sand of the upper clay at an altitude of about 50 feet and a few feet above the contact with the unnamed gravel.

A bed of fossiliferous massive silt 2 to 6 feet thick is exposed in the upper clay in a sea cliff along Puget Sound at West Point at an altitude of 30 feet. The bed dips gently to the southeast and passes below sea level on the south side of Magnolia Bluff about 2 miles southeast of West Point. Pelecypods collected by H. H. Waldron from this bed at West Point (NW¼NE¼ sec. 16, T. 25 N., R. 3 E.) have been identified as Anadonta cf. kennerlyi Sea by E. F. Trumbull, U.S. Geological Survey. Living species of Anodonta are found in several fresh water lakes in Washington today, and are restricted to depths of 0 to 20 feet.

The upper clay may be correlative with the Kitsap clay member (Sceva, 1957, p. 17-19) and the Pilchuck clay member of advance outwash of the Vashon drift (Newcomb, 1952, p. 18-19).

Unnamed Sand

A deposit of predominantly medium to coarse grained, slightly oxidized, stratified sand, which locally is as much as 220 feet thick (pl. 2, sec. C-C'), overlies the upper clay in the Seattle, West Seattle, and interlake drift plains. It is best exposed in the Seattle drift plain, where it consists chiefly of well-sorted medium-grained sand composed of quartz and rock fragments, and lenses of gravel, silt, and clay.

The unnamed sand is well exposed in the sea cliff at Fort Lawton near West Point, where its contact with the upper clay is at an altitude of about 100 feet. A few feet above the contact the sand is brown fine grained, and ripple marked. Higher in the section and extending to the top of the bluff, the sand is medium grained. The general character and distribution of the sand in the West Point area suggest that it was deposited in a large lake. In other exposures, however, such as in a sand pit in the NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 4. T. 25 N., R. 4 E., the sand is coarser grained and crossbedded.

The sand probably is correlative with the lower part of the Esperance sand member of advance outwash of Vashon drift (Newcomb, 1952, p. 18-23), and with the Puyallup sand.

Vashon Drift

The latest glaciation of the Puget Sound lowland by northern ice was termed the Vashon glaciation by Willis (1898, p. 126). Gravel, sand, silt, clay, and boulders deposited by the Vashon glacier are widespread in northwest King County and in the aggregate are commonly over 150 feet thick. The rock fragments are subrounded to subangular in shape; apparently nearly all were stream worn before being incorporated into the glacier. Stones that have become flattened or striated by glacial action are rare. Boulders tend to be more angular than the pebbles and cobbles.

Although the Vashon glacier originated in British Columbia (Bretz, 1913, p. 17), central Cascade rock types (Crandell, Mullineaux, and Waldron, 1958, p. 385) are common in its deposits in northwest King County. Only among the large boulders do the northern rock types predominate. Commonly, only about 15 percent of the stones, (pink granite and metamorphic rocks), contained in Vashon till and outwash are of the type derived from the northern Cascades and the Coast Range of British Columbia. The remainder of the stones are principally volcanic and white granitic rocks derived from the central Cascades. The predominance of central Cascade rock types apparently is due to the glaciers incorporating in the drift large quantities of locally derived stream alluvium. On the Newcastle Hills and the neighboring hills to the east the drift also contains pebbles of sandstone and shale, derived locally from the Tertiary sedimentary beds.

In this report the term "glacial drift" or "drift" follows the usage of Flint (1957, p. 108): "*** the term 'glacial drift' embraces all rock material in transport by glacier ice, all deposits made by glacier ice, and all deposits predominantly of glacial origin made in the sea or in bodies of glacial meltwater ***" For the purpose of this study, drift of the Vashon glaciation has been subdivided into three major units. Drift that is unsorted and virtually unstratified is termed till. Sorted drift is termed stratified drift. Stratified drift that was deposited as the glacier advanced is called advance stratified drift, and that deposited as the glacier retreated is called recessional stratified drift.

Vashon till and recessional stratified drift commonly can be distinguished from pre-Vashon unconsolidated deposits by topographic form. Because the glaciation of Vashon age is the most recent in northwest King County, almost all areas characterized by ground-moraine or ice-contact topography are underlain by Vashon drift.

Vashon drift, where composed chiefly of sand and gravel, often may be distinguished from pre-Vashon deposits by its fresh appearance. The sand and gravel deposits of pre-Vashon age generally are oxidized to a darker color than deposits of Vashon age. Pre-Vashon clay and silt have not been noticeably altered and commonly cannot be distinguished from clay and silt of Vashon age.

The sand and gravel bodies of pre-Vashon age commonly contain a cream-colored, very sticky clay. Locally, the Vashon stratified drift also contains clay that is similar in appearance, although it is not sticky. In general, the Vashon drift is not as indurated as is the pre-Vashon material. This distinction is not evident, however, in some outcrops of fine-grained materials.

Lithologically, the Vashon advance stratified drift is indistinguishable from the recessional stratified drift in most exposures. In some areas, however, the recessional drift has been slightly stained by post-Vashon weathering and this stain aids in discriminating the two units. The topographic expression of the recessional drift is a very useful mapping criterion. In many areas, however, the stratigraphic position of the stratified drift in relation to the Vashon till is the only criterion by which it can be identified.

Advance stratified drift.--Vashon advance stratified drift was deposited almost entirely by glacial melt-water streams. Some of the advance stratified drift was therefore deposited beyond the limits of the glacier and some was deposited in immediate contact with the ice such as in ice-dammed lakes or in deposits built by streams flowing along the margins of the glacier. However, only a few exposures contain features that indicate where the glacial ice stood while the advance stratified drift was being deposited in a particular locality.

The appearance of the Vashon advance stratified drift is variable, ranging in grain size from silt to coarse gravel, and in degree of sorting from well sorted to unsorted. However, it consists principally of sand to cobble gravel, and locally contains thin beds of laminated fine-grained material.

Deltaic beds are exposed in a road cut about 3 miles west of Fall City and 0.4 mile southwest of the Aldarra Farms buildings in the NW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 7, T. 24 N., R. 7 E., where a fine- to very fine-grained well-sorted sand shows ripple marks and compound foreset bedding. The individual foresets are about 2 inches high and the individual lamina are less than one-eighth inch thick. The sand is over 25 feet thick and contains numerous steeply dipping sand dikes up to half an inch thick and spaced about 1 foot apart. The delta apparently was formed by local drainage into a lake that occupied the Snoqualmie River valley. The surface of the lake probably was at an altitude of about 300 feet.

The advance stratified drift of this report is, in general, correlative with the upper part of the Esperance sand member (Newcomb, 1952, p. 18-23).

Till.--A virtually unsorted, unstratified compact mixture of boulders, cobbles, pebbles, sand, silt, and clay, as much as 150 feet thick (pl. 2), mantles most of northwest King County. Physically the mixture is similar to slightly rotten light-gray concrete and is appropriately called hardpan by well drillers.

Very little of the till is noticeably bedded although it commonly has a horizontal fissility. A shallow brown weakly podsolic soil is developed on much of the till of Vashon age (Poulson and others, 1952, p. 95). Impure iron oxide pellets, usually less than one-fourth inch in diameter, are abundant in this soil.

The Vashon till of Newcomb (1952, p. 23-25) and Sceva (1957, p. 20-23) is, in general, correlative with the Vashon till of this report; however, till-like materials mapped as Esperance sand member by Newcomb in southern

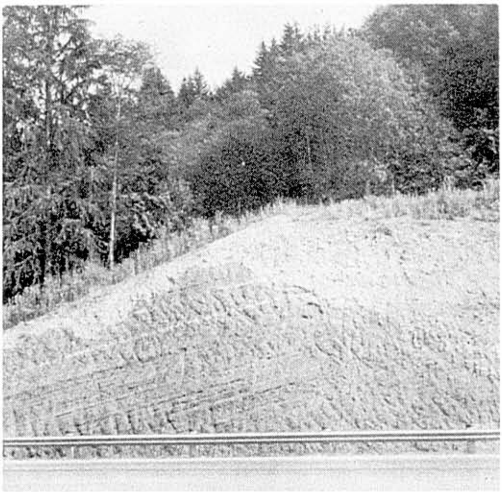

Figure 4.--Laminated clay of the Vashon drift, overlain by recessional stratified drift exposed along the south side of U.S. Highway 10, about 1 mile east of Issaquah.

Figure 5.--Vashon recessional stratified drift in a gravel pit about 1 mile north of Issaquah.

Snohomish County have been mapped as Vashon till by the authors of this report in northern King County.

Recessional stratified drift.-- Poorly sorted to well-sorted, light-gray, stratified gravel and sand containing minor amounts of silt and clay were deposited by the wasting Vashon glacier in isolated areas on the drift plains, on the Newcastle-Grand Ridge hills, and in nearly continuous sheets in the major valleys. The thickness of this material ranges from a featheredge to more than 100 feet (pl. 2).

Much of this recessional stratified drift was deposited in immediate contact with wasting ice, forming kame terraces, kames, and eskers. Kame terraces are present only above an altitude of 160 feet (Bretz, 1913, p. 166). One of the larger kames in King County is centered in the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 12, T. 24 N., R. 6 E. The upper surface of the kame is interrupted by a large kettle.

The only eskers recognized in northwest King County are just north of this kame and are in secs. 1, 2, and 12, T. 24 N., R. 6 E. The largest of these eskers is parallel to a road in the eastern part of the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 2, T. 24 N., R. 6 E., and extends southeast into secs. 1 and 12.

Recessional stratified drift laid down in front of the retreating glacier includes valley trains and lake deposits. Valley trains are present in many of the minor valleys, including those of Bear Creek northeast of Redmond, Bear Creek north of Woodinville, North Fork of Issaquah Creek, and Swamp Creek near Kenmore.

Extensive glacial-lake deposits occur in northwest King County. Large ice-dammed lakes that occupied the major valleys have been described in detail by Bretz (1913, 122-171). Silt and clay mantles the bottom and sides of these glacial-lake basins. In the NE$\frac{1}{4}$ sec. 17, T. 24 N., R. 6 E., more than 10 feet of this recessional lacustrine silt is exposed on the south side of a paved road. In the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 27, T. 24 N., R. 6 E., along the south side of U.S. Highway 10, about a mile east of Issaquah, clay and silt beds that have a moderate eastward dip (fig. 4) are exposed. These clay and silt beds may have been deposited on ice and when the ice melted were tipped to the east.

Streams emptying into these lakes laid down deltas of well-sorted gravel and sand. The larger deltas are shown on the geologic map (pl. 1). Gravel pits provide excellent exposures of the structure of the delta in sec. 27, T. 24 N., R. 6 E., near Issaquah (fig. 5). The Vashon recessional deposits to which Newcomb (1952, p. 26-28) applied formal names in Snohomish County do not extend into northwest King County.

Post-Vashon Deposits

In northwest King County post-Vashon deposits extensively underlie the Duwamish, Sammamish, and Snoqualmie River valley floors and a few isolated bodies of post-Vashon alluvium are associated with small streams on the uplands. The deposits, which consist of sand, silt, clay, and some gravel, commonly are over 50 feet thick and were laid down primarily by stream, lake, and marine processes. The greatest known thicknesses of these deposits in northwest King County are in the Snoqualmie River valley near the Snohomish County line and at the north end of the Duwamish River valley. Of these two places the thickness is inferred to be greatest in the Snoqualmie River valley. According to the owner of well 26/7-6D1, the blue clay penetrated at 340 feet is identical to the blue clay at the surface. The entire 340 feet of material may be post-Vashon in age.

Post-Vashon lake deposits occur in places where closed depressions were left by the Vashon glacier, in lakes formed as a result of glacial damming of the rivers in the area, and in Sammamish Lake and Lake Washington. The lake deposits are predominantly clay, silt, sand, peat, and muck. Landscapes sculptured by glaciers contain many closed depressions which are conducive to peat deposition. Consequently the occurrence of peat is common in all the Quaternary nonglacial sediments that were deposited when the climate was relatively mild. Peat consists of the remains of plants that accumulated in water or in wet places. Most of the plants whose remains formed the peat grew where the peat now lies. According to Rigg (1958, p. 5), "The plants may have been large or small, varying from large trees to algae and fungi." The plant remains may have undergone very little change, or they may have become disintegrated and decomposed. When decomposition is so complete that recognition of plant remains is no longer possible, the material is known as muck instead of peat (Rigg, 1958, p. 10).

Moss peat (sphagnum), fibrous peat (mostly sedge), woody peat, and sedimentary peat were recognized in northwest King County and their general distribution was described by Rigg (1958, p. 69-95). Peat is at the surface of more than 2,000 acres in northwest King County. The largest peat bog is about half a mile southeast of Bellevue and covers 535 acres. Rigg found the peat in this bog to be at least 50 feet thick.

A 1- to 2-inch layer of pumicite is present in most of the peat deposits of the area, and presumably was deposited over all the area; except in protected areas, however, subsequent erosion has removed or modified the layer. According to Rigg and Gould (1957), this layer is a record of a violent eruption of Glacier Peak which occurred approximately 6,700 years ago. They believe (p. 354, 356-362) that the accumulation of peat commenced about 10,000 to 14,000 years ago.

Post-Vashon deposits of northwest King County include much slump block material along valley walls, particularly in areas where sand of great thickness overlies clay. Two of the larger blocks are in the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 25, T. 25 N., R. 3 E., at the southeast end of Kinnear Park, and in the NE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 22, T. 26 N., R. 4 E. The scope of this investigation precluded the delineation of slump blocks and none are included with the post-Vashon deposits shown on plate 1.

Geologic History

The conditions governing the occurrence of ground water can be accurately determined only if the nature of the rock materials lying at depths likely to be reached by wells is known. In a geologically complex area, such as northwest King County, study of rock exposures and well records will not yield sufficient information to permit predicting the lateral extent and nature of rock units at some distance from the places where they are exposed. It is therefore necessary to learn as much as possible about the sequence of geologic events that have taken place in the area, and to relate the exposed rocks to these events. When the mode and sequence of deposition of the various rock units are known it is possible to understand and predict their occurrence and water-bearing character over a large area.

Pre-Quaternary History

The pre-Tertiary and part of the early Tertiary history of northwest King County have not been reconstructed as a part of this investigation because of inadequate information. For a generalized geologic history of the State of Washington, reference is made to Culver (1936), and Weaver (1937).

In late Eocene time over 12,000 feet of carbonaceous shale, dark and light-colored sandstone, coal beds, andesitic tuff, and volcanic breccia accumulated on a gradually sinking coastal plain in the present site of northwest King County (Warren and others, 1945).

During Oligocene and Miocene times the area was the site of a marine embayment in which about 8,000 feet of shale, sandstone, and conglomerate accumulated. Extrusion of the Keechelus andesitic series probably took place concurrently with the deposition of these sediments (Warren and others, 1945). Late in Miocene time northwest King County was uplifted and warped into northwest-trending folds. Newcastle Hills and the adjacent high buttes to the east are remnants of one of these folds. In Pliocene time the north-trending Cascade Mountains were uplifted. This movement continued into the Pleistocene epoch and present-day seismic activity indicates that it may be continuing. Shortly after the beginning of this uplift, erosion formed the major drainage of the Cascade Mountains. Physiographic expression of the earlier northwest-trending structure is found in the direction of flow of the upper reaches of many of the principal rivers that drain the northern and central Cascades.

Quaternary History

A change to a climate suitable for the development of glaciers occurred in Pleistocene time. Valley glaciers developed in the Cascade and Olympic Mountains (Bretz, 1913, p. 221-225); however, none of these alpine glaciers are known to have extended into the project area. Pleistocene deposition is represented in northwest King County by many hundreds of feet of unconsolidated clay, silt, sand, gravel, till, and peat. These beds are a complex succession of lacustrine, glacial, and marine deposits. According to Crandell, Mullineaux, and Waldron (1958, p. 384) at least four distinct major glaciers developed in Canada and moved into the Puget Sound lowland. Three glaciations were inferred from the reconnaissance mapping of northwest King County. One of these, the Vashon glaciation, was correlated with the Vashon of Crandell, Mullineaux, and Waldron in the southeastern part of the Puget Sound lowland. Neither of the other two could be correlated with any of their three pre-Vashon glaciations.

Interglacial erosional interval.--According to Bretz (1913, p. 195-220), the major valleys of the Puget Sound lowland were cut by streams consequent on a depositional plain during the nonglacial interval immediately preceding the Vashon glaciation. During this period, regional uplift elevated western Washington at least 1,000 feet above present altitudes (Bretz, 1913, p. 226), resulting in accelerated stream erosion and oxidation of the rock material.

Bretz (1913, p. 203) postulated that the King County area was drained late in pre-Vashon time by a master river flowing north through the main arm of Puget Sound. According to him, the Cedar River was then tributary to the Snoqualmie River, and together they cut the Snoqualmie River trough prior to Vashon glaciation.

Bretz attributed the origin of the troughs now occupied by Sammamish Lake and Lake Washington to a river that existed during the interglacial erosional interval and that headed in the south end of the present Sammamish Lake valley. The river flowed north through the Sammamish River valley, then west to the north end of Lake Washington through the valley near Bothell, then to the Puyallup River near Tacoma. The valleys formed during the interglacial erosional interval were greatly modified by the Vashon glacier.

Advance and maximum of the Vashon glacier.--The last glacier which extended into the southern Puget Sound lowland probably began advancing from its area of accumulation in British Columbia early in Wisconsin time, according to Waldron and others (1957). None of the contemporaneous valley glaciers in the Cascades or Olympics extended downvalley far enough to merge with the Vashon lobe at its maximum (Bretz, 1913, p. 221-225); instead, Vashon ice actually thrust up into some of these mountain valleys.

The advancing Vashon glacier dammed north-flowing streams in northwest King County and formed lakes. As the Vashon glacier moved over the northwest King County area, streams of meltwater flowing from the sediment-laden ice deposited stratified stream and lacustrine drift deposits. Till was plastered over much of the surface. The north-trending valleys, which were parallel to the direction of ice flow, were deepened (Bretz, 1913, p. 219) but in valleys lying transverse to the direction of ice flow, drift accumulated to a considerable thickness.

At its maximum, the ice reached a thickness of over 4,000 feet in the King County area (Bretz, 1913, p. 36) and extended about 15 miles south of Olympia, about 60 miles south of Seattle. The Vashon glaciation in the south and central parts of the Puget Sound lowland consisted of a single advance and retreat, with only one recognized minor oscillation (Bretz, 1913, p. 141). Extensive deposits of sand, gravel, and till were deposited by the heavily sediment laden ice.

Bretz stated (p. 227): "At the time of the maximum Vashon glaciation, the region stood at about its present altitude. The time of lowering from the interglacial higher altitudes may have preceded or been contemporaneous with the advance of the Vashon ice epoch; it was attained at least by the time outwash reached Grays Harbor at the mouth of the Chehalis."

Wasting of the Vashon glacier.--About 14,000 years ago the front of the Vashon ice lobe began melting back (Rigg and Gould, 1957, p. 358). This recession was accompanied by heavy runoff from the wasting ice, and many streams established themselves upon the surface of the ice, depositing gravel along walls of the marginal drift plains.

The major valleys which drained to the north became sites of a series of ice-dammed lakes. The altitudes of the surface of the lakes were controlled by the altitude of the lowest available spillway on the rimming valley walls. Evidence of these lakes is afforded principally by shoreline features, channels cut across the uplands, silts mantling the valley walls, deltas composed of Vashon recessional gravels built out into the valleys, and other shoreline features. Bretz, in 1910 and again in 1913 (p. 109-171), described this complicated Vashon recessional lake history. The two drift plains separating the valleys occupied by Lake Washington, Sammamish Lake, and the Snoqualmie River slope generally to the north. Thus, as the southern terminus of the ice damming the mouths of the latter two valleys wasted back, the ponded melt water was able to escape through progressively lower routes across these uplands. As the Vashon ice mass was thinning, the ice became stagnant and kame terraces, kames, kettles, and eskers formed in contact with the glacier. The locations of some of these features are given on page 17.

In addition to the ice-controlled lakes which were largely restricted to the northwest King County area, a very extensive ice-dammed lake occupied much of the Puget Sound lowland south of the Strait of Juan de Fuca. This lake was recognized by Bretz (1910, p. 458), who named it Lake Russell. The water surface of Lake Russell ranged in altitude from 160 feet to 120 feet during most of its history, the higher altitude prevailing (Bretz, 1913, p. 109-171). The surface of Lake Russell constituted the base level in the area, and in referring to Puget Sound, Bretz comments (p. 166), "No kame terraces of the region are known below the 160-foot contour. Several well-developed terraces end at about this level, and the topography of the gravel becomes very subdued where the deposit is continued farther down the valley."

Post-Vashon Geologic History

Removal of the Vashon ice from the area left an uneven, pitted topography favorable for the accumulation of small lakes such as Cottage Lake in sec. 7, T. 26 N., R. 6 E., and Phantom Lake in sec. 2, T. 24 N., R. 5 E. In both these lakes, as well as in many other lakes in the area, tens of feet of peat accumulated. Most of these peat bogs, in common with many other peat bogs in Washington, contain a thin volcanic ash bed (described earlier, p. 18). The wind-blown volcanic ash probably settled over much of the State, but subsequent erosion and mixing has removed and obscured it except in deposits laid down in standing water. Pollen analysis of the peat reveals a nearly continuous change of climate, from a cool-moist period immediately after the Vashon retreat through a period of warming and drying, to another cooler and moister climate of the type that exists today (Hansen, 1947, p. 113-118).

The topography in the Puget Sound lowland area has been modified only slightly by erosion since the end of the Vashon glaciation. Outflow from springs and runoff from the uplands have cut steep-sided canyons in the major valley walls and have transported the material to the major valleys where the lower gradient caused these small streams to drop part of their suspended load. Alluviation has developed flat floors in the major valleys. The Tolt River, which discharges into the Snoqualmie River valley southeast of Carnation, has built a fan across the valley, deflecting the Snoqualmie River to the west side of the valley. The combined lateral erosive action of the two rivers at their confluence has steepened a 400-foot cliff in the west slope of the valley. Slumping has steepened many of the slopes extending from the uplands to the main valleys, and waves have eroded many of the slopes overlooking Puget Sound.

Manmade Alterations

Regrade projects in Seattle have involved movement of millions of cubic yards of Pleistocene sediments, and have completely obliterated much preexisting topography. Bretz (1913, p. 174), in discussing the Denny Hill regrade project, states "*** it (Denny Hill) was removed by hydraulic methods from more than 20 city blocks, the maximum cut being 125 feet."

The Lake Washington canal was cut through between Lakes Washington and Union in 1916 and Lake Washington was lowered from 22 feet to 14 feet above sea level. Cedar River formerly flowed either into the south end of the lake or through the Black River into the Duwamish River, its course depending on the course of the delta distributary. The canal is now the outlet of the lake, and the Cedar River's entire discharge now enters the lake. The Black River channel was abandoned and is now a slough. The former Lake Washington beach extends around the lake as a terrace.

Summary of the Geologic History

Following is a chronologic summary of the salient events that have influenced the terrain of northwest King County and vicinity:

Tertiary:

A. Late in the Eocene epoch over 12,000 feet of carbonaceous shale, sandstone, coal beds, andesitic tuff, and volcanic breccia accumulated on a gradually sinking coastal plain.

B. During the Oligocene and Miocene epochs about 8,000 feet of marine shale, sandstone, and conglomerate were deposited, probably concurrently with the extrusion of andesitic flows of unknown thickness.

C. Commencing late in Miocene time, the area was deformed by folds trending approximately N. 70° W.

D. The north-trending Cascade and Olympic Mountains were uplifted in the Pliocene.

Quaternary:

E. The Puget Sound basin was partially filled by at least three periods of glaciation separated and followed by lacustrine, alluvial, and marine deposition of clay, silt, sand, gravel, and peat.

F. Relative uplift of the Puget Sound basin resulted in a period of canyon cutting. Much of the present depth and width of the Puget Trough, and the valleys occupied by Lake Washington, Sammamish Lake, and the Snoqualmie River may have been formed during this period.

G. Advance of the Vashon glacier in Wisconsin time deepened and widened north-trending valleys. Thick bodies of sand, gravel, and till were deposited over the area, particularly in valleys transverse to the direction of ice movement.

H. Retreat of the Vashon ice occurred at least 14,000 years ago. A series of ice-dammed finger-shaped lakes eroded spillways across the uplands. Ice-contact stratified drift was deposited over much of the area.

I. Period of alluvial valley filling and localized peat deposition, minor erosion, and soil development.

GROUND WATER

Water in Consolidated Rocks

Of the consolidated rocks of Tertiary age in northwest King County, only sedimentary rocks of Oligocene and Miocene ages are known to yield water to wells. Although the volcanic rocks, and particularly the sedimentary rocks of Eocene age, may yield appreciable quantities of water--as indicated from reports of water problems in coal mines producing from Eocene sedimentary rocks--these rocks have not been explored as possible sources of ground water. In those areas where considerable ground-water development has taken place, these rocks are overlain by Quaternary deposits that yield ground-water supplies adequate to meet the present demand.

In the Newcastle Hills where Quaternary materials are thin or absent (pl. 2, secs. A-A', C-C', pl. 1), water is obtained from sedimentary rocks of Oligocene and Miocene ages. Fieldwork in the Newcastle Hills showed that sandstone and conglomerate beds possibly as much as 1,000 to 2,000 feet thick crop out near the crest of the northeast flank. The outcrop area of these beds, which strike about N. 75° W. and dip about 45° NE., is the principal area of recharge for these deposits.

Wells drilled in the Newcastle Hills updip from the sandstone and conglomerate outcrops have not proved successful. Wells drilled on the flank of the hills far enough northeast of the outcrops to penetrate a substantial thickness of saturated sandstone and conglomerate yield economic quantities of water. Only two wells are known to have been drilled high on the northeast flank of Newcastle Hills updip from the sandstone outcrops. Of these, well 24/5-25B1 was drilled to a

The yields of wells in northwest King County that tap older unconsolidated deposits range from a few gallons per minute to more than 700 gpm. Large yields generally are obtained only where a substantial thickness of sand or gravel is encountered. For example, well 24/4-18B1, which taps about 120 feet of water-bearing sand and gravel in the older unconsolidated deposits between 165 and 1,030 feet below the land surface, yields about 100 gpm. Well 25/5-32N1 which produces from older unconsolidated deposits, chiefly sand, yields about 450 gpm with a drawdown of 65 feet, indicating a specific capacity of almost 7 gpm per foot of drawdown. The coefficient of transmissibility is about 15,000 gpd per foot. Because the occurrence of sand and gravel in the older unconsolidated deposits is unpredictable, considerable risk will be involved in any attempt to develop a large water supply from this unit.

The greatest concentration of wells tapping older unconsolidated deposits is in Tps. 24 and 25 N., Rs. 4 and 5 E. Probably as many as 40 wells in these townships tap older unconsolidated deposits, and 9 of them (table 5) flowed when drilled. Artesian conditions in the older unconsolidated deposits are not limited to these townships, however; flowing wells tapping these deposits have been reported in many other parts of the project area. Most such flowing wells are less than 100 feet above sea level.

Locally, at least, some wells tapping older unconsolidated deposits have produced water with an objectionably high chloride content (p. 47).

Lower Clay Unit

The lower clay unit yields little water to wells in northwest King County. It acts as an impermeable floor below the younger water-bearing units, and locally may cause perched water bodies in the overlying unnamed gravel. In other places, where sand or gravel deposits are at or near the top of the underlying older unconsolidated deposits, the lower clay may confine water under artesian conditions in them.

Unnamed Gravel

High permeability, thickness of as much as 200 feet, and wide areal extent of the unnamed gravel combine to make it one of the most productive aquifers in northwest King County. Because it occurs at relatively low topographic positions, the unnamed gravel commonly is saturated throughout most or all of its thickness. Discharge of large quantities of water at exposures is retarded by the relatively impermeable weathered exposures. The unnamed gravel is tapped by wells in practically all parts of northwest King County, except in the major valleys and in upland areas underlain at shallow depths by Tertiary rocks. The principal development of ground-water supplies from the unnamed gravel, however, has been in the east drift plain and the interlake drift plain. The average depth to water in wells tapping the unnamed gravel in these two areas is about 135 feet. Because of the variation in thickness of the unnamed gravel, these wells range in yield from a few to as much as several hundred gallons per minute. The average yield of wells tapping the unnamed gravel is about

150 gpm. Well 25/5-5R1 taps 102 feet of unnamed gravel and yields 390 gpm with 19 feet of drawdown. Well 25/5-5H1, which taps 68 feet of unnamed gravel, yields about 150 gpm with a drawdown of about 21 feet.

Upper Clay Unit

The upper clay unit is not a productive aquifer in northwest King County, and many wells have penetrated its entire thickness without encountering material capable of yielding appreciable quantities of water. For example, wells 24/5-7K1, 25/5-23F2, and 26/4-1E1 penetrated the entire thickness of the upper clay unit (140, 60, and 89 feet, respectively) without encountering sand or gravel. Only locally does this clay contain thin lenses of sand and gravel which may yield as much as a few tens of gallons of water per minute. Wells 25/5-14J1 and 26/5-17D1 are typical of those which yield water from the upper clay. Well 25/5-14J1 penetrates 192 feet of this material; the upper 66 feet is principally clay, the next 122 feet is mainly fine sand, and the lower 4 feet is gravel. The well yields 25 gpm with a drawdown of 2 feet. Well 26/5-17D1 penetrates at least 228 feet of upper clay; 218 feet of this is clay, fine sand, and silt. The well yields 25 gpm from a sand bed 10 feet thick at about 270 feet below the land surface.

Unnamed Sand

Where saturated, the unnamed sand provides adequate supplies of water for domestic use. Spring discharge and evapotranspiration commonly drain the sand along the margins of the uplands; therefore, the greatest thickness of saturated unnamed sand commonly is beneath the central area of the uplands. Well 26/5-11K2, about 1 mile east of Woodinville on the west side of the east drift plain, penetrates 150 feet of Vashon till, 167 feet of unnamed sand, and 10 feet of the upper clay unit. The upper 160 feet of the unnamed sand is unsaturated. Well 26/5-19L2, about 1 mile east of the west margin of the interlake drift plain and about $1\frac{1}{2}$ miles northwest of Juanita, penetrates 140 feet of Vashon till, 210 feet of sand and gravel--the bulk of which may be Vashon advance stratified drift--and 44 feet of lower clay. The upper 165 feet of the sand and gravel is unsaturated.

Although the wells that tap the unnamed sand range widely in yield, it is common for them to yield at least enough water for domestic use or for small public supply. The yields of wells 25/5-21Q1, 26/4-13G1, and 26/4-30J1 are typical. The U.S. Geological Survey made an aquifer test at well 25/5-21Q1, which is 100 feet deep and penetrates the upper 20 feet of a bed that is probably the unnamed sand; the casing is perforated from 90 to 100 feet below the land surface. At 50 gpm the drawdown was 24 feet and the coefficient of transmissibility was computed to be 6,600 gpd per ft. Well 26/4-13G1 is 62 feet deep and penetrates the unnamed sand from 18 to 62 feet below the land surface. Although only the lower 2 feet of sand is saturated, the well yields a supply ample for domestic use. Well 26/4-30J1, 238 feet deep, penetrates 72 feet of unnamed sand. The well has a drawdown of 160 feet when pumped at the rate of 190 gpm. Fine sand in troublesome quantities occasionally is carried into the casings of wells tapping the unnamed sand. This difficulty usually can be eliminated, or at least minimized, by careful selection of well-screen slot size.

Vashon Drift

Advance stratified drift

The advance stratified drift generally yields large supplies of water to relatively shallow wells; however, its distribution is erratic and its occurrence can seldom be predicted with accuracy. Where it is deeply eroded, as along the margins of the drift plains, the advance stratified drift may be largely unsaturated owing to discharge by springs. A typical spring discharging from advance stratified drift is 25/6-17N1s (table 6) which yields 25 gpm.

Hydrologic data for four wells tapping the advance stratified drift are listed in table 1. Of the four, well 24/6-27D2 is the most productive in the project area. The data indicate a wide range in water-bearing character of the zones tapped.

Till

In most places the upper part of the Vashon till is more permeable than the compact lower part. Where this situation exists the upper part may contain a perched or semiperched water body that will yield small quantities of water to shallow wells. The lower portion retards the downward percolation of water. Examples of shallow wells that tap water in the upper part of the Vashon till are 25/5-26J1 and 26/4-24A1. Both are less than 50 feet deep and yield sufficient water for domestic use.

Nearly all the wells that produce from till are for domestic use. Many of these are reported to yield inadequate quantities of water, particularly during summer and fall. This seasonal failure to obtain water from till may be due to dewatering, by pumping of isolated lenses of sand and gravel having low rates of recharge, or it may be due to discharge of water from shallow, perched ground-water bodies by evaporation and transpiration. Because water occurs usually at a relatively shallow depth in the till, small supplies can be developed cheaply; however, the aquifer is very susceptible to contamination.

Recessional stratified drift

Water can be obtained almost everywhere in northwest King County from the recessional stratified drift. Large yields are obtained where a considerable thickness of coarse-grained material occurs within the zone of saturation. Well 24/4-12M1, on the north end of Mercer Island, which taps terraced recessional stratified drift, penetrated 62 feet of sand and gravel before encountering hardpan. Although only the lower 26 feet of material is saturated, the well yields 600 gpm with a drawdown of only 5 feet. Some of the wells in the lower end of Bear Creek

Table 1.--Selected wells that tap only Vashon stratified drift

Well	Inferred thickness of Vashon stratified drift penetrated (feet)	Screened or perforated interval (feet)	Pumping rate (gallons per minute)	Elapsed pumping time (hours)	Drawdown (feet)	Specific capacity (gallons per minute per foot of drawdown)	Transmissibility (gallons per day per foot)
24/6-27D2	16	11	730	---	0.6	1,200	--------
24/7-10C1	27	24	150	0.3	3	50	--------
25/5-12C1	14.5	5	45	1	1	45	100,000
25/5-20C1	188	184	500	1	48	10	22,000

valley and in the Sammamish River valley at Redmond tap recessional stratified drift composed of well-sorted gravel which has a maximum thickness of more than 30 feet. All these wells have large yields. For example, dug well 25/6-6F1, 13 feet deep, yields 60 gpm and has a drawdown of less than 1 foot. The aquifer transmissibility as indicated by testing this well may be as great as 350,000 gpd per foot.

Yields sufficient for domestic use are obtained at many places on the uplands where the drift contains semiperched ground-water bodies. For example, wells 26/5-20C1, 21 feet deep, and 26/5-12A1, 17 feet deep, on the interlake and east drift plains both yield sufficient water for domestic needs throughout the year.

Post-Vashon Deposits

Many wells tap highly permeable gravel lenses in the upper 20 feet or so of alluvial deposits which underlie the floors of the major stream valleys. Most of the shallow wells that draw water from alluvium in the Snoqualmie and Sammamish River valleys were constructed for domestic and (or) stock use, and in general they yield ample quantities of water for this purpose. For example, well 26/5-27K1, which taps alluvium on the west side of the Sammamish River flood plain near York is only 15 feet deep but is reported to yield 200 gpm.

A comparatively inexpensive method of developing a water supply from alluvium is provided by several driven well points connected to a single pump. Six such points, designated well 23/4-4B1 in table 5, are driven into the alluvium to depths of 17 to 22 feet. The yield of this system is adequate for the operation of 12 irrigation sprinklers, and is used during the summer months to water commercially grown vegetables.

Recent slump blocks, marine and lacustrine sediments, and lacustrine peat and muck are not known as a source of ground water in northwest King County. Locally, peat and muck may have an adverse effect on water quality because they probably add humic acid to the ground water. The acid tends to cause the water to be corrosive, to have a marked color, and to promote the solution of iron and perhaps other undesirable constituents that are present in the rock materials through which the water percolates.

Water in the Drift Plains

The occurrence of ground water in the drift plains west of the Snoqualmie River is discussed in this section; the area east of the river, termed the "Cascade foothills" in this report, is not discussed. In this study the emphasis was placed on the area to the west; the foothills were not investigated intensively enough to allow a reliable evaluation of their ground-water features.

On the drift plains the wells of larger yield tap gravel beneath the Vashon till. Although small to moderate supplies of water for domestic use are obtained at many places from dug wells less than 50 feet deep that tap perched or semiperched water bodies in Vashon till or recessional stratified drift, the yields may become inadequate in summer. Where saturated, however, the recessional stratified drift commonly yields water adequate for domestic use throughout the year. Many of the numerous springs along the edges of the drift plains have been developed for domestic and public supply.

West Seattle Drift Plain

Drillers' logs of wells that were drilled in the West Seattle drift plain a few miles south of the boundary of the project area indicate that moderate to large yields can be obtained from unconsolidated deposits that extend to or below sea level. In that part of the West Seattle drift plain within the northwest King County area (fig. 1), the greatest thickness of saturated sand and gravel probably is near the south boundary of the area and greater yields probably could be expected from wells in the southern part of the drift plain than in the northern part.

Well 23/4-5Q1, 55 feet deep, in the southern part of the drift plain--a quarter of a mile north of the south boundary of the area--is reported to yield 150 gpm. Wells 23/3-1P1, 65 feet deep, and 24/3-13F1, 472 feet deep, were drilled in the northern part of the drift plain. Well 23/3-1P1 did not yield water in economic quantity, and the yield of well 24/3-13F1 could not be determined. No longer used, the well was drilled for practically its entire depth into older unconsolidated deposits, and penetrated significant thicknesses of permeable material in only the bottom 46 feet. This well, at an altitude of 30 feet near Elliott Bay, is on the east edge of the drift plain. Wells drilled in the higher parts of this plain may penetrate water-yielding materials stratigraphically higher than those penetrated by this well (see pl. 2, sec. C-C').

Seattle Drift Plain

Practically all the development of ground water in that part of the Seattle drift plain north of Lake Washington Canal is north of T. 25 N. In this area, wells ranging in depth from about 10 to 50 feet yield small quantities of water from Vashon till. Locally along McAleer Creek valley, small yields are obtained from shallow wells tapping Vashon recessional stratified drift.

Most wells in this area obtain water from Vashon advance stratified drift and the unnamed sand, in substantial quantities. For example, well 26/4-30K1 yields 600 gpm, and is one of the largest yielding wells in this part of the Seattle drift plain. It is 260 feet deep and taps a 170-foot interval of Vashon advance stratified drift and unnamed sand. The average depth of wells tapping Vashon advance stratified drift in the northern part of the Seattle drift plain is about 90 feet.

Wells on or near the margins of the drift plain generally do not penetrate thick saturated zones of Vashon advance drift, and the yield from that aquifer is sometimes supplemented by drilling deeper to penetrate the unnamed sand or the unnamed gravel. The water-bearing capabilities of the unnamed gravel, however, are unpredictable; in the northern part of the Seattle drift plain it ranges in thickness from 0 to about 100 feet, and the grain size as well as the degree of compaction and cementation also is variable.

Several of the wells in the northern part of the Seattle drift plain are believed to tap the older unconsolidated deposits, which in this area lie at altitudes ranging from about 35 feet above sea level to about 50 feet below sea level. The amount of water obtained from them is not known.

The wells of highest yield in the southern part of the Seattle drift plain are located in the north-trending topographic trough between Interbay and Queen Anne hill. Well 25/3-14J1, the northernmost of these wells, taps gravel and sand between 376 and 502 feet below the land surface. This material may be part of the older unconsolidated deposits. The well yields 765 gpm, with a drawdown of 61 feet, indicating a specific capacity of about 13 gpm per foot of drawdown. Well 25/3-23Q1, about $1\frac{1}{4}$ miles south of well 25/3-14J1, taps two sand and gravel zones. The upper zone, 53 feet thick, was penetrated at 251 feet below the land surface; the lower zone, 112 feet thick, was penetrated at 635 feet. The upper zone is probably part of the unnamed gravel, and the lower zone is inferred to be part of the older unconsolidated deposits. This well yields 450 gpm, with a drawdown of 89 feet, indicating a specific capacity of about 5 gpm per foot.

The remainder of the wells in the southern part of the Seattle drift plain are within about a mile of Elliott Bay. Well 25/4-30R1 yields 150 gpm from the unnamed gravel in the interval 291 to 521 feet below the land surface.

The range in yield of five wells in the area is from 65 to 250 gpm. The well of lowest yield has a drawdown of 100 feet and a specific capacity of less than 1 gpm per foot. No yield data are available for other wells. No wells are known to have been drilled south of these in the Seattle drift plain and for that reason ground-water conditions to the south must be inferred solely from the rock materials exposed (pl. 1). Data are available from seven wells in sec. 31, T. 25 N., R. 4 E., all within a few hundred feet of Elliott Bay (pl. 3). Four of these are reported to yield water containing objectionable quantities of chloride, which may indicate local encroachment of sea water (p. 47).

Interlake Drift Plain

Adequate ground-water supply for domestic and small public needs can be developed in practically all parts of the interlake drift plain. Wells range in depth from less than 10 feet to more than 1,000 feet and average about 82 feet. The average depth to water in these wells is about 37 feet, and the average reported yield is about 75 gpm.

Small supplies of ground water are obtained locally from Vashon recessional stratified drift. The average depth of wells tapping this aquifer is about 22 feet, and the average depth to water is only about 8 feet. These yield about 6 gpm on the average. Vashon till is tapped by a large number of dug wells. However, many of them are reported to be inadequate for domestic use in the late summer and autumn.

In the interlake drift plain, the Vashon advance stratified drift or the unnamed sand occurs almost everywhere except in some of the deeper valleys and along the margins of the plain. Most wells on this drift plain tap aquifers in one or both deposits. However, the thickness and permeability of these aquifers varies greatly from place to place, resulting in a great range in yield of the wells tapping them, from a few gallons per minute in well 25/5-26H1 to about 250 gpm in well 24/5-10C2. The average yield of wells tapping these deposits is 28 gpm, an amount well in excess of that required for domestic use. The average depth of wells tapping aquifers in the advance stratified drift or the unnamed sand is about 63 feet, and the average depth to water is about 38 feet, a situation that renders development of ground water for domestic use fairly economical in all places where the thickness of these aquifers is appreciable.

Small ground-water supplies are obtained locally from wells tapping sand in the upper clay unit. These wells average about 100 feet in depth and are located principally around the margins of the drift plain where the Vashon advance stratified drift is too thin to be an important aquifer.

The unnamed gravel is fairly continuous under the interlake drift plain, and is capable of yielding large amounts of water to wells. Wells tapping this aquifer average about 145 feet in depth, and the average depth to water is about 80 feet. The average reported yield of wells tapping the unnamed gravel in the interlake drift plain is about 200 gpm.

The older unconsolidated deposits are tapped by wells principally along the margins of the interlake drift plain where more water is needed than can be obtained from the younger deposits. The average depth of wells tapping the older unconsolidated deposits on the interlake drift plain is about 350 feet. Although the average yield of these wells is about 235 gpm, many of them also obtain some water from the overlying younger deposits, and the proportion obtained from the older deposits is not known. Because of artesian conditions in the older unconsolidated deposits, the average depth to water in wells tapping these deposits--about 45 feet--is less than the average depth to water in wells tapping the unnamed gravel or the upper clay.

Eastern Drift Plain

In the eastern drift plain little difficulty has been experienced in developing ground-water supplies because in most places one or more of the aquifers above the lower clay is present and is of sufficient thickness and permeability to yield water adequate to meet the small needs of the area. Wells in the eastern drift plain range in depth from less than 10 to 353 feet, and average about 80 feet. The average depth to water in these wells is about 45 feet, and their average reported yield is about 30 gpm.

On much of the drift plain, small quantities of water can be obtained from shallow wells tapping Vashon till. Most of these wells are large-diameter dug wells. Here, as elsewhere in northwest King County, many are reported to be inadequate for domestic needs in the summer and autumn when water levels are low.

Locally in the eastern drift plain, especially in the north half, yields of as much as 100 gpm are obtained from shallow wells tapping recessional stratified drift. The yield of such wells varies greatly, according to the permeability and thickness of saturated material penetrated. The average depth to water in wells tapping Vashon till or recessional stratified drift is about 15 feet.

More wells in the east drift plain obtain water from Vashon advance stratified drift than from any other aquifer. The unnamed sand was not recognized at the surface in the east drift plain, and all sand or gravel overlain by Vashon till and underlain by the upper clay or older units is considered to be Vashon advance stratified drift. The yield of wells tapping this advance stratified drift is usually adequate for domestic supplies throughout the entire year, and in most of the area the aquifer is tapped by only moderately deep, drilled wells--their average depth is about 110 feet.

In the eastern drift plain where the younger aquifers are not present or are unproductive, and where relatively large ground-water supplies are needed, wells are drilled deep enough to obtain water from the upper clay or the unnamed gravel. The average depth of wells tapping one or both of these aquifers is about 220 feet, the average depth to water is about 110 feet, and the average reported yield is about 30 gpm.

Several wells in the eastern drift plain are believed to tap older unconsolidated deposits. These wells range in depth from 183 to 353 feet; however, because of artesian conditions in the older unconsolidated deposits the average depth to water in these wells is less than that to water in wells tapping the upper clay or the unnamed gravel.

Water in the Major Valleys

The floors of the major river valleys range in altitude from sea level to slightly over 100 feet; the principal aquifers are in unconsolidated material of Vashon and Recent ages and they lie at depths of as much as 300 feet below the valley floors. The wells tapping these aquifers range in yield from a negligible amount to more than 500 gpm. Except in the Duwamish River valley, the quality of ground water is satisfactory for most uses; there the chloride content is high. Locally elsewhere, well owners report that the iron content of water from their wells is objectionably high.

Although much of the unconsolidated material penetrated by wells drilled in the major valley floors is clay, silt, and fine sand, sand and gravel bodies which yield small to large quantities of water to wells occur where large melt-water streams emptied into the major river valleys during Vashon time. The two sand and gravel bodies about which considerable geologic and hydrologic data are available are at the mouths of East and North Forks of Issaquah Creek near Issaquah, and at the mouths of Bear and Evans Creeks near Redmond. Issaquah Creek flows into the south end of Sammamish Lake and Evans Creek is a tributary of Sammamish River.

Areas in which melt-water stream deposits occur, but in which little evidence exists for sand and gravel bodies that are restricted to the tributary stream junctions, are the mouths of Raging River near Fall City, Tolt River near Carnation, and Cherry Creek near Duvall.

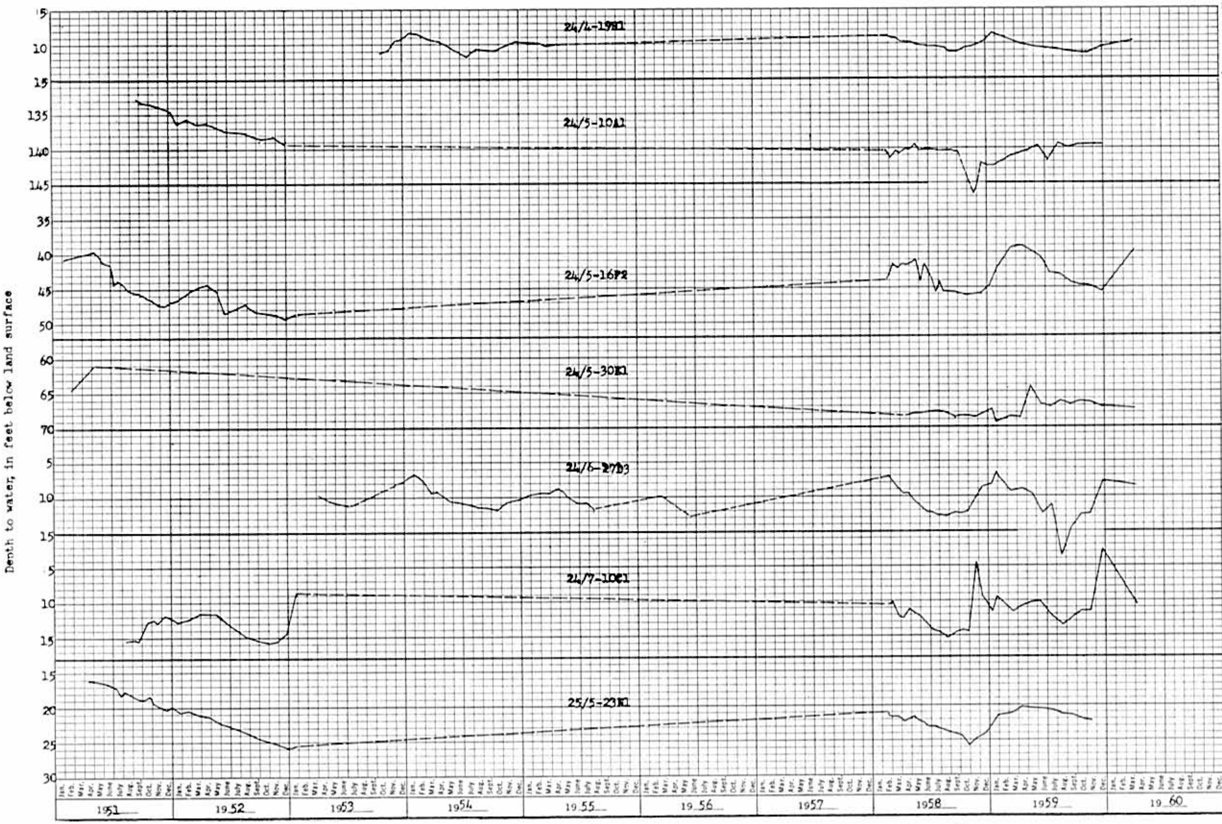

Figure 6.--Hydrographs showing fluctuations of water levels in observation wells.

Figure 7.--Hydrographs showing fluctuations of water levels in observation wells.

Duwamish River Valley

The Duwamish River valley floor is here considered to be that portion of the valley that is less than 25 feet in altitude and that is south of Yesler Way and east of Duwamish Head. Wells on the valley floor obtain water from the valley alluvium or from aquifers in the older unconsolidated deposits beneath the alluvium.

Of the wells listed in table 5, only seven are on the Duwamish River valley floor. Well 23/4-4B1 is a system of driven sand points ranging in depth from 17 to 22 feet, and is used for irrigation. A sample of water from this system contained 83 ppm of chloride. The other six wells range in depth from 240 feet (24/4-7G1) to 1,550 feet (24/4-18B1). Well 24/4-18B1 had a drawdown of 170 feet when pumped at 100 gpm. This yield was not sufficient to meet the needs of the owner, the Elliott Bay Mill Co. Well 24/4-8D1 was drilled to 232 feet and, according to the driller, the only water-bearing material was a 1-foot-thick gravel bed at 215 feet. Well 24/4-5E1, the only well on the Duwamish River valley that is still in use, is reported to yield 42 gpm; no record of its depth or of the materials it penetrated is available.

Water from wells 23/4-4A1 and 24/4-19H1 contained 348 and 990 ppm of chloride, respectively. Water from well 24/4-7G1 was incrusting and contained flammable gas and hydrogen sulfide.

Sammamish River Valley

The two most productive aquifers beneath the Sammamish River valley floor (fig. 1) are in the neighborhood of the large Vashon recessional stratified drift deltas at Issaquah and Redmond. Both underlie hardpan and probably are bodies of Vashon advance stratified drift. Wells 24/6-27D1, -27D2, and -28J1, at Issaquah, range in depth from 46 to 58 feet and in yield from 400 to 730 gpm. Their range in specific capacity is from 19 to 1,200 gpm per foot. Wells 25/5-12C1, 25/6-6E1, and -6F1, at Redmond, range in depth from 13 to 56 feet and in yield from 60 to 200 gpm, with specific capacities of 100 to 200 gpm per foot.

Periodic water-level measurements in well 24/6-27D3 (fig. 6) in the aquifer at Issaquah, and in well 25/6-6F1 (fig. 7) in the aquifer at Redmond, indicate no decline in the period 1953-59. Because a large supply of surface water is in contact with the aquifers and available for induced recharge, it is safe to assume that pumpage from these aquifers could be greatly increased with virtually no chance of overdevelopment. These aquifers are among the most promising sources of water for the expanding population of Seattle and its suburbs.

Elsewhere in the Sammamish River valley, yields are much smaller, though quantities sufficient for domestic use may generally be obtained at depths of less than 75 feet.

Snoqualmie River Valley

Of the wells listed in table 5, 11 are in that portion of the Snoqualmie River valley that is south of the Tolt River. The yield of these wells ranges from

300 gpm from the southernmost (24/7-15F1) to a quantity inadequate for domestic use from the northernmost (25/7-29H1). These wells all tap post-Vashon stream deposits of varying thickness. Some of the difference in yield can be attributed to the type of construction of the individual wells; however, the difference is probably due in large part to the material becoming progressively finer grained northward from Fall City. No data are available concerning wells on the Snoqualmie River valley upstream (southeast) from Fall City. It is not known, therefore, whether the coarser material was deposited by the Snoqualmie River or by the Raging River, which joins the Snoqualmie at Fall City.

Records are available for only two wells, 25/7-15M1 and -6R1, on the Snoqualmie River valley between the mouth of the Tolt River and Duvall. Well 25/7-15M1, about half a mile north of the Tolt River, is 101 feet deep and yields 96 gpm with a drawdown of only 2 feet. This well penetrates much more permeable material than is commonly found in this part of the Snoqualmie River valley and may tap deltaic beds deposited by the Tolt River. Well 25/7-6R1 is 630 feet deep and flows about 280 gpm. Although on the valley floor, it is near the valley wall and probably penetrates only a few feet of post-Vashon stream deposits overlying older deposits.

Several test holes more than 200 feet deep are reported to have penetrated only fine-grained materials having very low yields.

Of the wells listed in table 5, six are in the Snoqualmie River valley between Duvall and the Snoqualmie County line. All penetrate only post-Vashon stream deposits. These wells, which range in depth from 206 feet near Duvall to 340 feet near the county line, penetrate principally blue clay, and obtain water from fine- to medium-grained gravel near the bottoms of the wells. Water levels in the six wells reportedly range from about 20 feet below the land surface to 13 feet above; all except 26/6-13D1 are reported to have flowed a few gpm when constructed. The water-bearing sand and gravel tapped by these wells probably extends south of Duvall also, but the southern limit is not known.

Water on Mercer Island

The conditions governing the occurrence of ground water on Mercer Island are complex. Except for recharge from Lake Washington to some of the older aquifers which lie below lake level, recharge is limited to that part of the precipitation on the island that infiltrates. If the rate of recharge to the aquifers above the level of Lake Washington is equivalent to 10 to 20 inches of precipitation, a recharge area of about 1 to 2 square miles would be required to furnish a continuous ground-water supply of 700 gpm, or 1 mgd (million gallons per day).

Well 24/4-12M1, near the top of a hill on the north end of Mercer Island, was drilled 62 feet into Vashon recessional stratified drift. The recessional drift here is very permeable, and during intermittent pumping the well reportedly yielded 600 gpm with 5 feet of drawdown. However, the sustained yield, which is limited chiefly to the natural recharge by precipitation on about one-fifth of a square mile, is probably between 75 and 150 gpm.

The unnamed sand and lenses of sand in the upper part of the upper clay are also above the level of Lake Washington and receive limited recharge. Wells tapping these aquifers on Mercer Island do not usually yield more than 15 to 20 gpm. Well

24/4-25B3, which extends about 67 feet below lake level and obtains water principally from the unnamed gravel, is pumped at a rate of only 25 gpm. At this rate, however, the drawdown was reported to be negligible after 40 minutes. Well 24/5-17D1 also extends below lake level (about 44 feet) and reportedly yields 42 gpm, probably from a sand lens in the upper clay. Pumpage of these two wells may induce recharge from the lake; thus they may not depend entirely on direct precipitation as the sole means of recharge. Locally, on the east side of Mercer Island, the unnamed gravel is absent or is above the level of Lake Washington and is unimportant as an aquifer. For example well 24/5-7J3 was drilled to a reported depth of 600 feet without encountering more than a small amount of water.

Water in the Newcastle-Grand Ridge Hills

Wells in the Newcastle-Grand Ridge hills obtain water both from bedrock and from unconsolidated deposits. The water-yielding characteristics of the bedrock have been discussed on pages 23 and 24. The Vashon drift probably is the source of water for many of the shallow dug wells. Two drilled wells in the hills, 24/6-28F1 and 24/7-21A1, tap unconsolidated deposits. Well 24/6-28F1, 197 feet deep, produces from a sand bed between 187 and 197 feet below the land surface and yields 20 gpm with 15 feet of drawdown. This sand bed is probably in the Vashon advance stratified drift.

Well 24/7-21A1 is 283 feet deep and yields 6 gpm from several pre-Vashon gravel beds penetrated between 184 and 257 feet below the land surface.

Use of Ground Water

Domestic Supplies

Most wells in the northwest King County area are used for individual domestic supplies. The average daily use is small, probably less than 500 gallons per well. The total number of such wells in the area is not known precisely; however, there probably are not more than 3,000, and their average total daily pumpage probably does not exceed 1½ million gallons.

Public Supplies

Most of the smaller public-supply systems in northwest King County obtain water from wells or springs. (See table 2.) Although data on the population served and the daily consumption could not be obtained for all systems, it is estimated that together they supply about 4 mgd to about 38,000 people.

The city of Seattle obtains its water supply from the Cedar River south of the northwest King County area. According to the Seattle Water Department's annual report for 1959, the city supply served an estimated population of 723,700 persons a total of 35 billion gallons of water during the year--an average of 133 gpd per person.

Table 2.--Use of ground water for public supply

Water-supply system	Source of supply	Storage capacity (gallons)	Population served	Number of customer connections	Consumption (gallons per day) Max.	Min.	Avg.
Baker Water System	24/5-18M1	5,000	--------	12	------	------	------
Benetho Beach Water Assoc.	24/5-31E1s	9,000	--------	17	------	------	------
City of Bothell	26/5-5E1 -5E2	105,000	1,775	600	------	------	165,000
Brewer Addition Water System	24/5-32J1	30,000	--------	13	------	------	------
City of Carnation	25/7-23P1s	-------	1,000	-----	------	------	------
City of Duvall	26/6-13D1	-------	290	100	------	------	------
Fall City Water Dept.	24/7-11L1s -15F1	220,000	--------	240	------	------	------
Hilltop Community, Inc.	24/5-23C1	-------	125	34	22,500	4,500	12,000
Horizon View Co., Inc.	24/5-23E1	-------	90	28	------	------	1,200
City of Issaquah	24/6-27Q1 -27Q1s	260,000	1,700	-----	------	------	275,000
King County Water Dist. 1, Yarrow Point	25/5-17F1	100,000	500	165	316,000	------	------
King County Water Dist. 22, Beaux Arts	24/5-8D1	30,000	340	99	64,000	19,000	------
King County Water Dist. 24, Richmond Beach	26/3-1M1 -1M2 -1M3 -1M4 -1M5	200,000	3,200	800	------	------	------

Table 2.--Use of ground water for public supply--Continued

Water-supply system	Source of supply	Storage capacity (gallons)	Population served	Number of customer connections	Consumption (gallons per day) Max.	Min.	Avg.
King County Water Dist. 72, Juanita	26/5-30G1	600,000	------	450	------	------	110,000
King County Water Dist. 82, Pine Lake	24/6-4N1	130,000	------	136	------	------	15,000
	-4N2						
King County Water Dist. 83, Lake Forest Park	26/4-3Q2	250,000	------	500	------	------	------
	-3Q5						
	-9C2						
	-9C3						
King County Water Dist. 97, Lake Hills	24/5-2D1	------	------	900	------	------	150,000
	-2D2						
City of Kirkland	25/5-17J1	------	13,300	3,600	------	------	930,000
	-17Q1						
	-17Q2						
	-17R1						
	-17R2						
	-5H1						
	-5R1						
Norwood Village Corp.	24/5-9C1	50,000	450	82	42,000	16,000	------
City of Redmond	25/5-1A1s	400,000	1,250	435	206,000	------	90,000
	-12C1						

Table 2.--Use of ground water for public supply--Continued

Water-supply system	Source of supply	Storage capacity (gallons)	Population served	Number of customer connections	Consumption (gallons per day)		
					Max.	Min.	Avg.
Washington Water Service Company	24/5-11N1 -11N2 -13M1 -23R2 -35A3 Sammamish Lake	------	6,000	------	------	------	75,000

Industrial Supplies

The supply of ground water used by industries in northwest King County is small; most of the industries are in Seattle and are furnished surface water from the municipal system. The small use of ground water undoubtedly is due in part to the concentration of industrial plants along Elliott Bay and the Duwamish River valley--areas in which ground-water supplies are difficult to obtain. Many wells in these areas have been unsatisfactory because of their low yields or the undesirable chemical quality of the water.

Ground water used by the Lakeside Gravel Co. near Issaquah accounts for more than half the ground water pumped by industries in the area. (See table 3.)

Irrigation Supplies

More than half the ground water pumped for irrigation in northwest King County is used for cemeteries and golf courses. The largest system is the consolidated one that serves Evergreen and Washelli Cemeteries. It has a capacity of 2,200 gpm and a 250,000-gallon storage reservoir. Data on this system and four others are presented in table 4. The average total yearly pumpage by the five systems listed in table 4 is estimated to be about 200 million gallons, from 10 wells. Table 5 lists more than 50 other wells, which are used partially or entirely for irrigation. These wells, which supply water for irrigation of greenhouse, nursery, and crops, probably have an average total yearly pumpage of less than 100 million gallons.

Fluctuations of Water Levels

The water table or the piezometric surface is not a static surface, but one that fluctuates in response to changes in the amounts of recharge and discharge, to changes in barometric pressure, and, near the coast, to tidal fluctuations. Fluctuations of ground-water levels that are more than a few tenths of a foot in amplitude are due usually to changes in the amounts of recharge and discharge.

Because of natural discharge and pumping from wells, water levels tend to decline except after those periods of precipitation when recharge exceeds discharge. The rapidity and magnitude of the recharge of ground water due to infiltration of precipitation depends largely upon the frequency, duration, intensity, and seasonal distribution of storms, the character of the vegetal cover, and the geologic and topographic environment. For a given rate of recharge the rate of decline of ground-water levels in an area is dependent upon the amount of pumpage, spring flow, underflow to nearby ground-water bodies, and evapotranspiration.

In order to determine the amount of fluctuation of water level in wells, periodic water-level measurements were made in 15 wells during the course of this investigation. The hydrographs of these wells (figs. 6-8) are arranged according to principal aquifers and to well-location numbers. A graph of the precipitation and the cumulative departure from normal precipitation at Seattle for the period 1951-59 appears in figure 8 for comparison.

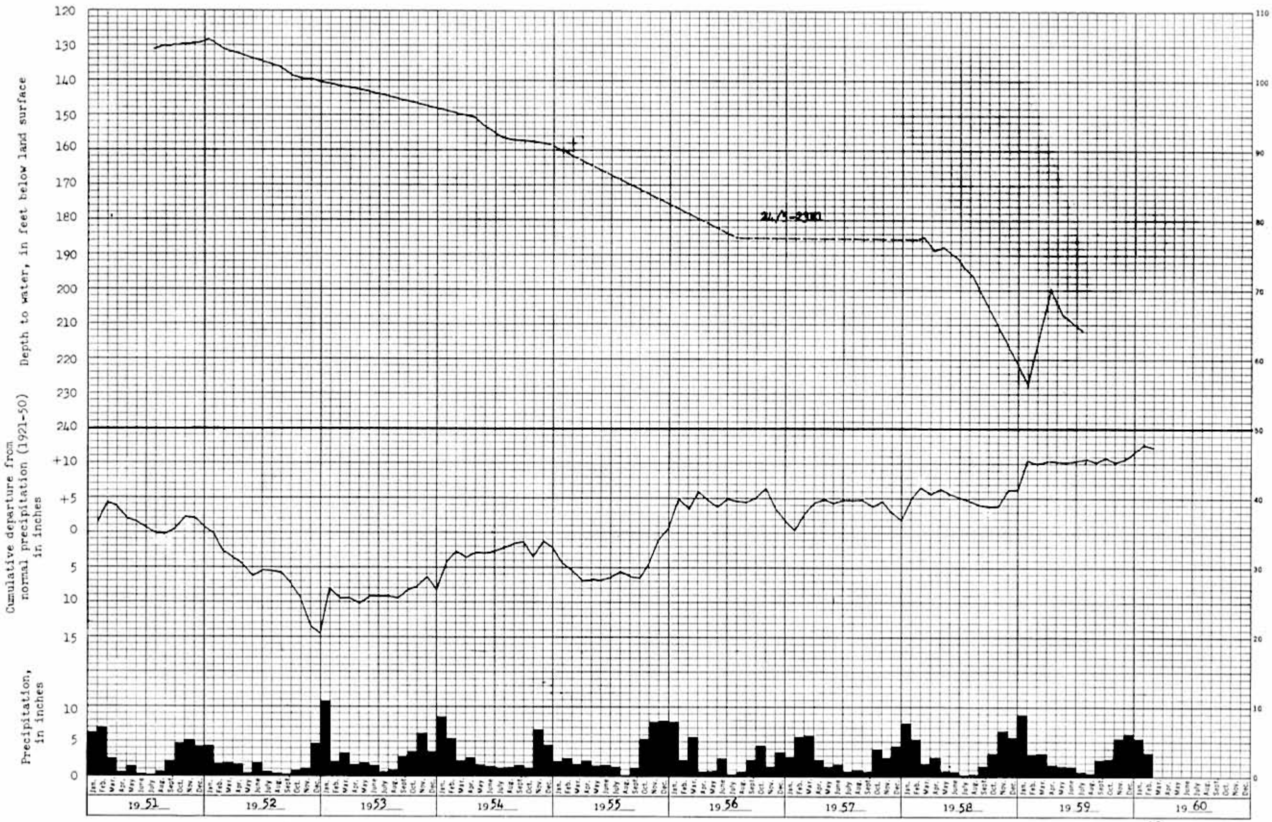

Figure 8.--Hydrograph showing fluctuations of water levels in well 24/5-23E1, monthly cumulative departure from normal precipitation, and monthly precipitation at the Federal Office Building, Seattle.

Table 3.--Use of ground water for industrial supply

Industry	Well(s)	System capacity (gpd)	Average consumption (gpd)	Remarks
Ballard Ice Skating Arena	25/3-11R1	--------	[a]40,000	
Booth Fisheries Corp.	25/4-31E1 -31E2	530,000	170,000+	Consumption is 170,000 gpd during winter, 530,000 gpd during summer.
Great Northern Ry. Co.	25/3-14J1	1,000,000(?)	[a]40,000	100,000-gallon storage tank.
Darigold Farms	24/6-28J1	700,000	400,000	10,000-gallon storage tank.
Lakeside Gravel Co.	24/6-27D1 -27D2 -27D3	1,900,000	1,000,000	
Pacific Fruit & Produce Co.	24/4-5E1	60,000	30,000	
Troy Laundry-Cleaners	25/4-30R1	--------	115,000	
University of Washington, Dept. of Fisheries	25/4-16D2	90,000	90,000	

[a] Estimated

Table 4.--Large ground-water supplies for irrigation

User	Well(s)	System capacity (gpm)	Acres irrigated	Maximum consumption (gpd)
Acacia Memorial Park Cemetery	26/4-16Q1	425	35	410,000
Evergreen and Washelli Cemeteries	-30C1	2,200	130	[a]1,500,000
	-30F1			
	-30J1			
	-30K1			
	-30K2			
Glen-Acres Golf Club	23/4-5Q1	150	50	[a]150,000
Holyrood Cemetery	26/4-5C1	350	25	80,000
	-5E1			
Sunset Hills Memorial Park	24/5-3G2	225	13½	1,100

[a] Estimated

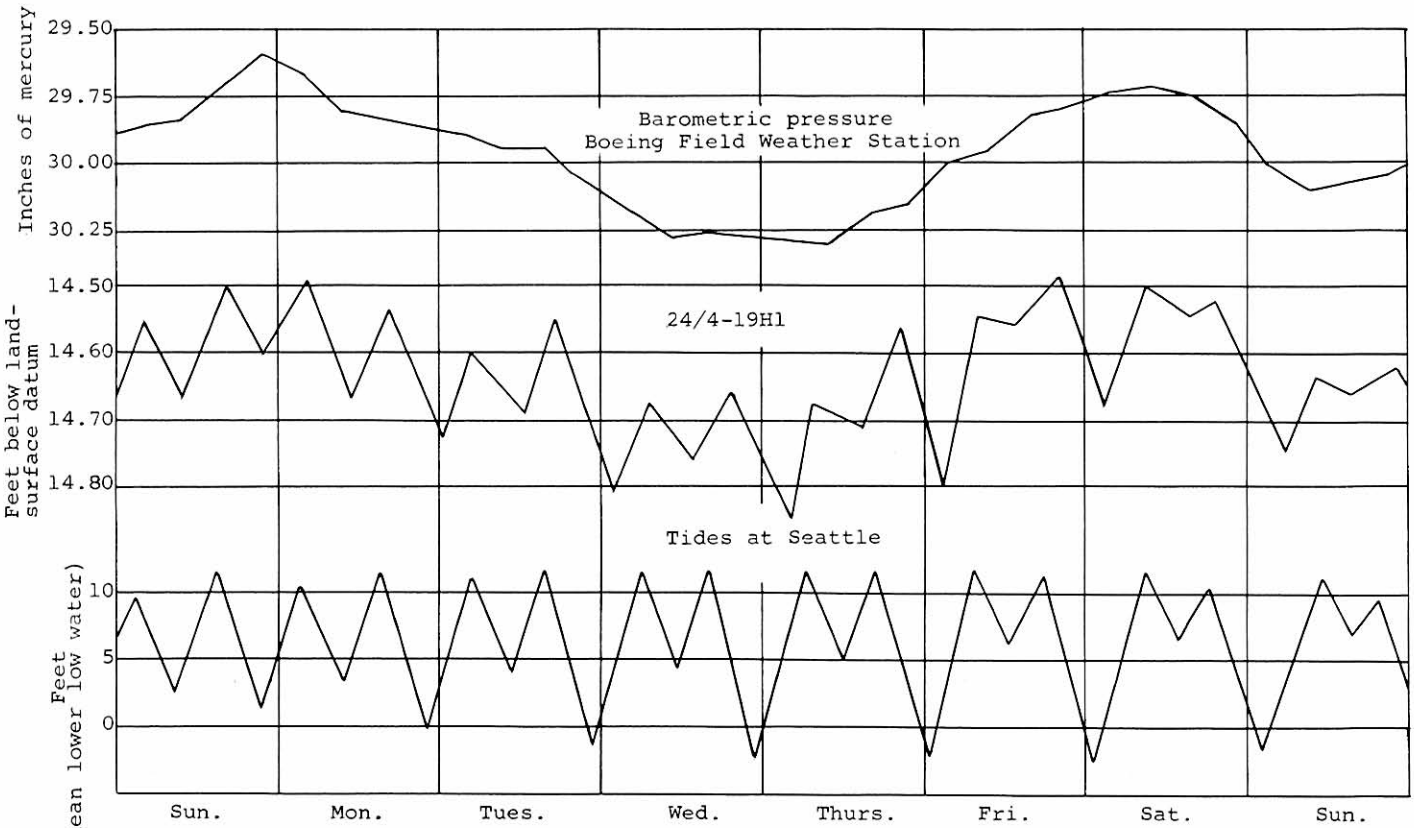

Figure 9.--Effect of barometric pressure and tidal fluctuation on water level in well 24/4-19H1, October 10-17, 1954.

Most of the hydrographs show a rise in water level within a few weeks or months after the rainy season begins. The period of low water level tends to occur in autumn and the period of high level tends to occur in spring or late winter. The effects of the below-normal precipitation in 1952-53 are evident in most of the hydrographs although they are most noticeable in the hydrographs of wells 24/5-10A1, -16F2, 25/5-23N1, and 26/5-21K1. The decline in water level in well 24/5 -23E1 probably results from local overpumping from an aquifer of low permeability rather than from reduced precipitation; there is no pronounced rise in water level in this well in response to increased precipitation during the years following 1953.

The fluctuations of water levels in wells in shallow unconfined aquifers are probably due largely to changes in rates of recharge during times of relatively constant discharge, whereas the fluctuations of water levels in the wells that tap confined aquifers, such as those in the advance stratified drift, are probably due to variations in pumping rates of nearby wells tapping the same zones, during times of relatively constant recharge.

Minor water-level fluctuations that range in amplitude from several hundredths to several tenths of a foot are due chiefly to earthquakes, to changes in barometric pressure, or to loading and unloading of the area by moving loads, such as passing railroad trains or tides.

The influence of the barometric pressure and tide changes on the water level in well 24/4-19H1 is shown by data plotted on figure 9. A time lag between high and low tides and the corresponding high and low water levels in the well is evident. The well is at an altitude of about 15 feet and is a hundred feet east of the Duwamish waterway.

Wells tapping artesian aquifers commonly function as inverted barometers. That is, ground-water levels decline in response to increasing barometric pressure, and rise in response to reduced barometric pressure. The fact that water levels in well 24/4-19H1 respond in this manner suggests that this well taps artesian or semiartesian aquifers.

Earthquake shocks usually result in an abrupt but very brief change in water level, and they can usually be detected only by examination of the chart of a continuously recording water-level instrument. In the course of this investigation, such instruments were maintained only for short periods of time and no disturbance due to an earthquake was detected on any of the graphs recorded during these periods.

Quality of Water

The chemical character of ground water in northwest King County and its general suitability for agricultural and domestic uses are discussed in this section. The discussion is based on 144 chemical analyses of water from wells and springs (tables 8 and 9).

Expression of Results

In the chemical analyses listed in table 8 and 9 the constituents are reported in parts per million. A part per million is one unit of weight of a constituent in a million unit weights of water. The results can be expressed in grains per U.S. gallon by dividing the results in parts per million by 17.12. When the chemical analyses of water are to be studied in detail, it is advantageous to report the results in equivalents per million. Equivalents per million for any constituent (or ion) can be obtained by dividing the concentration of the constituent in parts per million by the chemical equivalent weight of the constituent.

Hardness is expressed in this report as calcium carbonate. In table 8, hardness is computed; in table 9, hardness is obtained by chemical analysis. Although hardness is listed in the results of the chemical analyses, it is, strictly speaking not a chemical entity (Hem, 1959, p. 146). In general, however, because total hardness supposedly represents the effects of all substances which react with soap, hardness data are valuable to those who use water for household purposes.

Geochemistry of Ground Water

Precipitation is derived from the condensation of water vapor on particles in the air, and it usually contains small amounts of mineral matter. When water enters the ground it dissolves minerals in varying quantities. Among the most important of the factors which determine the character and concentration of mineral constituents in ground water are the mineral composition of the rocks through which the water passes and the length of contact time within them.

Ground water is primarily a solution of bicarbonates, chlorides, and sulfates of the alkaline earths, calcium and magnesium, and of the alkalies, sodium and potassium. Other constituents often present, but usually in much smaller quantities, are silica, iron, manganese, flouride, nitrate, phosphate, boron, heavy metals, hydrogen sulfide, and carbon dioxide.

The proportions of each ion present determine the chemical type or classification of a water. In northwest King County, on the basis of the comprehensive chemical analyses listed in table 8, most of the analyses represent water of the alkaline earth (calcium-magnesium and magnesium-calcium) bicarbonate type. A few deeper wells, however, yield water of the sodium chloride type.

Relation of Water Quality to Use

In determining whether the ground water in northwest King County is acceptable for all types of use, the analyses are referred to a set of standards for comparison. For drinking water the generally accepted standards of quality are those of the U.S. Public Health Service (1946). According to those standards, certain substances should not be present in excess of the concentrations shown as follows:

	ppm
Fluoride	1.5
Lead	.1
Arsenic	.05
Selenium	.05
Hexavalent chromium	.05

An excessive concentration of any of the above elements constitutes a basis for rejection of the supply. If the water is acceptable on the basis of constituents mentioned, it is evaluated according to the following less restrictive upper limits for other constituents:

	ppm
Copper	3.0
Iron and Manganese (together)	.3
Magnesium	125
Zinc	15
Chloride	250
Sulfate	250
Phenolic compounds (as phenol)	.005
Total dissolved solids	
Water of good quality	500
Where no better water is available	1000

Of the elements tabulated in the first of the foregoing two lists, only fluoride was determined for most of the samples whose analyses are shown in table 8. Of those in the second list, iron, magnesium, chloride, sulfate, and total dissolved solids were determined for most of the samples whose analyses are shown in tables 8 and 9. For the remaining constituents in both lists, no information is available.

Although a study of the areal occurrence of iron was not made during the course of this investigation, fragmentary information collected in the field suggests strongly that there may be a relation between the existence of objectionable quantities of iron in water from some wells and the proximity of these wells to peat deposits. Most of the peat of Recent age and probably at least some of the pre-Vashon peat is acidic. The circulation of ground water through peat materials is likely to render it acid, making it possible for the water to react with iron minerals. The reaction is usually of such type that the iron content of the water is thereby increased.

Iron in water in excess quantity is objectionable chiefly because a precipitate of ferric hydroxide, formed by oxidation of ferrous bicarbonate, produces a reddish or brown stain on porcelain, enameled ware, and clothing. A high iron content also imparts to the water an objectionable taste.

In northwest King County, the chloride content of water is low. Of the 144 samples analyzed, the chloride content is less than 20 ppm in all but 8. Only 5 contain chloride in excess of the acceptable limit of 250 ppm. For the area as a whole, chloride content is significant in that if it is above, say 25 ppm, it may indicate contamination, either by sea water, by deep-seated connate water, or by organic or inorganic wastes.

Water from only 6 wells contain more than 500 ppm of dissolved solids, the acceptable limit for water of good quality. For most of the waters the dissolved-solids content is below 200 ppm. Of the analyses listed in table 9, about 60 percent are for water in which dissolved-solids content is less than 100 ppm.

Nitrate determinations are included in 30 of the analyses listed in table 8. The nitrate content in all the waters tested for this constituent is well below the acceptable limit. In the water from well 26/3-1D3, however, the nitrate content is sufficiently high as to suggest the possibility of contamination.

The hardness of water from 58 of the wells or springs whose analyses are reported in tables 8 and 9, is 50 ppm or less. The hardness of water from 13 wells, about 9 percent of the total for which hardness is reported, is more than 100 ppm. For the area as a whole, the water is acceptable from the standpoint of hardness.

The usefulness of a water for irrigation also is dependent on the chemical quality of the water. The standards of water quality are, however, much different for irrigation use than for household use. According to the U.S. Salinity Laboratory Staff (1954, p. 69-82), some of the important factors that determine whether a water can be used for irrigation without causing plant or soil damage are the dissolved-solids content, the proportion of sodium to the other cations, and the concentration of individual constituents in the water. The total concentration of salts should be less than that equivalent to a specific conductance of 2,250 micromhos (1,350 to 1,600 ppm); the sodium hazard is low if the sodium-adsorption ratio [a/] is less than 10 for waters whose specific conductance is less than 250 micromhos; the boron

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[a/] Sodium-adsorption ratio and residual sodium carbonate are determined by the following relations where ion concentrations are expressed in equivalents per million.

$$\text{Sodium-Adsorption ratio (SAR)} = Na^{+}\left(\frac{Ca^{++} + Mg^{++}}{2}\right)^{-\frac{1}{2}}$$

$$\text{Residual sodium carbonate} = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++})$$

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content should be less than 1 to 2 ppm, depending on the type of plant to be irrigated. The U. S. Salinity Laboratory Staff (1954, p. 81) also reports that water with more than 2.5 equivalents per million of residual sodium carbonate [a/] are not suitable for irrigation.

On the basis of the foregoing criteria 6 wells in northwest King County yield water of questionable quality for irrigation. These wells are listed below:

Well number	Reason for Questionable Quality
23/4-4A1	SAR, 35; dissolved solids, 872 ppm.
24/4-6A1	Analysis not adequate for evaluation; dissolved solids, 537 ppm.
24/4-19H1	Dissolved solids, 2,360 ppm.
24/5-4D1	SAR, 10; residual sodium carbonate, 5.4 epm; dissolved solids, 963 ppm.
25/4-31E1	Dissolved solids, 1,320 ppm.
25/4-31R1	Analysis not adequate for evaluation; dissolved solids, 1,055 ppm.

Of these 6 wells, only 1 is in an area currently being irrigated or of irrigation potential. Because the lateral extent of the water-bearing zones yielding water to this well is not known within close limits, the development of additional ground-water supplies for irrigation in this area should be accompanied by careful chemical analysis of the water prior to application.

Of all the water analyzed for boron, none contain more than the acceptable limit of 1 to 2 ppm.

Water of Inferior Quality

Water from a few wells in northwest King County contains enough dissolved solids as to be worthy of discussion. Water from each of the 8 wells in the following list contains more than 250 ppm of dissolved solids; all except 3 contain more than 250 ppm of chloride.

Well number	Depth (feet)	Dissolved solids (ppm)
23/4-4A1	686	872
23/4-4B1	17	[a]/360
24/4-6A1	180	537
24/4-19H1	631	2360
24/5-4D1	600	963
25/4-31E1	785	1320
24/6-18E1	40	[a]/430
25/4-31R1	145	1055

[a]/Computed from specific conductance

Of the remaining two wells, a comprehensive water analysis is available only for the one near Bellevue. This well, 24/5-4D1, is unique because of its high content of both bicarbonate and chloride and its comparatively low sulfate content. This well is the deepest ever drilled in the Bellevue area for which a chemical analysis is available--the unusual chemical character may result from contact with a possible connate water existing at depth in this area. According to White (1957, p. 1,666) connate water is rich in silica and is low in sulfate and magnesium relative to sea water. The character of the water from this well conforms with these criteria rather closely. However, further study would be required to verify such a possibility.

The water from well 24/6-18E1, 40 feet deep, is unusual in that its bicarbonate content, 752 ppm, is the highest of any water tested in northwest King County. Only a partial analysis is available (table 8) and it is not possible to compare the chemical character of this water with any of the others for which comprehensive analyses are available. Its low hardness, 58 ppm, indicates that the water must be very rich in sodium, a feature known to exist in waters from deep zones. The geologic features of the immediate area suggests that the water from well 18E1, in common with that from 24/5-4D1, may be a blend of meteoric and connate waters.

Future Development of Ground-Water Supplies

Tertiary rocks will probably always be of secondary importance as a source of ground water in northwest King County. In most parts of the area, as was pointed out earlier, the Tertiary rocks are too deeply buried to permit economical development of the relatively small supplies afforded by these rocks. Water-level measurements in well 24/5-23E1 (fig. 8) over a 9-year period indicate that locally on the Newcastle hills, where Tertiary rocks are the principal aquifers, the rate of ground-water withdrawal possibly has exceeded the rate of recharge.

Hydrographs of 14 wells for the 10-year period 1951-60 indicate that there has been no serious overdraft from aquifers in the unconsolidated deposits of northwest King County, and pumpage from these aquifers probably could be increased severalfold without seriously depleting the amount of water in storage. Although relatively large ground-water supplies may be developed locally from the older unconsolidated deposits, the unpredictability of the occurrence of permeable zones in this unit, and the presence, at least locally, of water of inferior quality probably will retard extensive development of ground water from these deposits. The unnamed gravel probably receives little direct recharge in northwest King County, and development of large ground-water supplies from this unit should be preceded by careful planning and testing to assure a continued dependable supply. The unnamed sand, Vashon advance stratified drift, and Vashon recessional stratified drift now discharge ground water at many exposures. By increasing the withdrawal from these aquifers the water level would be lowered and some of the natural discharge would be salvaged. These aquifers, where exposed at the surface over large areas, may now be rejecting recharge from precipitation during the winter. Greater development of the ground-water resources of these areas and the resultant lowering of the water table would permit the salvaging of recharge that is now being rejected. Additional ground-water development along the course of perennial streams that are now receiving ground-water discharge from permeable materials would result in reversal of the ground-water gradient, and the stream would then recharge the ground-water body.

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